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DEPARTMENT of TRANSPORTATION

DIVISION OF
ENGINEERING SERVICES

MATERIALS ENGINEERING
AND TESTING SERVICES

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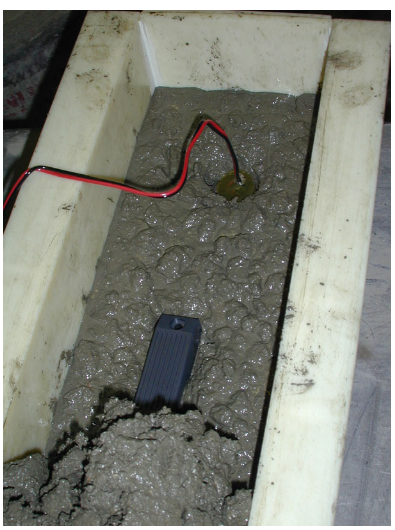

VERIFICATION TO IMPLEMENT CONCRETE MATURITY REQUIREMENTS IN CALTRANS SPECIFICATIONS

STATEWIDE

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This report reflects the observations, findings, conclusions, and recommendations of the Office of Rigid Pavement Materials and Structural Concrete. This report does not constitute a standard, specification, or regulation.

This report was conceived by Caltrans' Office of Rigid Pavement Materials and Structural Concrete and their consultants, Applied Research Associates, Inc. – ERES Consultants Division. Testing was performed at the Materials Engineering and Testing Services laboratory at 5900 Folsom Boulevard, Sacramento, California 95819.

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ORGANIZATION OF THE PROJECT REPORT

Chapter 1 of this report introduces the project, the need for this research, and its scope and objectives. Chapter 2 provides an overview of concrete maturity concepts and the use of maturity as a quality control and quality acceptance tool. Chapter 3 describes the development of a test plan and experimental design for the lab study that was carried out. Chapter 4 discusses the analysis of data collected during the experimental stage and the results of the analysis performed. The final chapter of this report, Chapter 5, provides a summary of the project and the conclusions drawn from the research effort.

Data collected in the experimental stage and the maturity calculations are presented in the appendices, as follows:

- Appendix A shows the mix designs used for these experiments.
- Appendix B contains the strength data generated from the strength tests conducted at Translab, for each mixture and for all testing ages.
- Appendices C and D contain the data related to maturity calculations using two different maturity models: the Nurse-Saul and Arrhenius methods, respectively.
- Appendix E presents a comparison of results between the current study and a study on implementing concrete maturity to predict flexural strength in concrete pavements conducted by the University of California. Note that one of the mix designs used in the latter study was identical to one of the mix designs used in the current project, thereby enabling a direct comparison of the raw data and test results.
- Appendix F provides a step-by-step procedure, using real test data as an example, to calculate maturity-based strength predictions.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Engineers have constantly sought methods to better evaluate and test materials to gain a more thorough understanding of their behavior, and to subsequently optimize designs or operational conditions as required. In particular, being able to assess the in-situ strength of a material would be extremely helpful for quality control and quality assurance procedures. In the case of concrete materials, a tool to assess in-situ strength could provide much needed information on the strength gain of a concrete mix. Accurate real-time strength data aids in defining appropriate times for formwork removal, joint sawing, and opening to traffic, etc. Moreover, it also is a factor in staging construction, scheduling construction and estimating construction workdays, and provides an insight into potential durability issues for the concrete during its service life.

Nondestructive test methods are the ideal test procedures to evaluate in-situ strength of concrete pavements and other concrete structures. Nondestructive testing is a general term used by engineers today to associate any form of testing that aids in evaluating the strength or performance of a material without causing any damage or detriment to in-situ structure. Concrete maturity is a nondestructive test concept, traditionally used for determining concrete compressive strength gain during the hydration process.

Concrete maturity technology has been studied and improved upon over the past five decades. Concrete maturity is a concept used to indirectly estimate the strength of a hydrating mixture based on its time-temperature history. The time-temperature history, measured in-situ, is used to predict a maturity index. Currently, two different maturity functions — the Nurse-Saul and the Arrhenius equations — are used to determine the maturity index that is correlated to concrete strength.

The model developed from lab-cured specimens is usually referred to as the strength-maturity relationship. This relationship is used to estimate the strength of the in-situ concrete, the time-temperature history of which is recorded in the field. This concept is explained in more detail in the ensuing chapters. The maturity method is an alternative to performing strength tests of companion cylinders or beams cast from the concrete mixture used in the construction process.

A serious limitation in using the traditional strength tests to assess the strength of in-situ concrete is the fact that the standard specimens, typically cast in sizes and volumes vastly different from the original structure, do not necessarily (or accurately) represent the in-situ strength values of the in-situ mixture. Furthermore, these standard cylinder or beam tests are performed at fixed points in time. This does not allow the identification of an exact point in the strength gain timeline when the required strength value is achieved.

The ability to overcome some of these limitations has made concrete maturity a highly favored and increasingly popular test method for use by contractors and owner agencies in quality control and quality assurance alike, as well as for fast-track projects. Several maturity meters are commercially available for performing concrete maturity tests.

The maturity method adopts a simple approach to predict strength values by continuously monitoring the temperature of a hydrating mix. The prediction is, however, influenced by the accuracy of the calibration model developed for the specific mixture under standard laboratory conditions. The test procedure most commonly adopted is the recently published ASTM Standard C1074-98, *Standard Practice for Estimating Concrete Strength by the Maturity Method*. Details about the Nurse-Saul and Arrhenius functions, and the research that led to the development of the ASTM standard, are briefly discussed in Chapter 2.

1.2 PROJECT REQUIREMENTS

Concrete maturity has been a widely researched topic for the last five decades and has been gaining wider acceptance, both in the United States and worldwide. For the past decade, the Federal Highway Administration has been encouraging State Departments of Transportation to evaluate the maturity method and to refine procedures and protocols for its use to fit the individual needs of the State. Several states have conducted such research and have already developed specifications and protocols that allow for the use of the maturity method.

The Office of Rigid Pavement Materials and Structural Concrete at Caltrans initiated this study to try to implement concrete maturity requirements for the State with a preliminary verification of the fundamental principles of maturity techniques. Furthermore, a thorough review of the literature indicates that the concrete strength parameter typically correlated to maturity is compressive strength. This strength parameter may well be the most suitable for applications to most reinforced concrete structures; however in California, the Caltrans design criterion for concrete pavements is concrete flexural strength, because it is the qualifying criterion intended to limit the development of fatigue cracks that can ultimately lead to pavement failure.

The strength criterion used for opening a concrete pavement to traffic, especially in projects with a limited construction time window, is also flexural strength. Caltrans specifications require that concrete pavement attains a minimum flexural strength of 610 psi (4.2 MPa) before allowing traffic on the roadway. In addition to strength, the Department mandates that no traffic be allowed on the concrete for 10 days. This requirement will be specified whether or not maturity methods are implemented for predicting concrete strength.

Strength predictions using concrete maturity require the development of a mix-specific calibration curve. The emphasis on the strength prediction model being specific to the mix is to enable the model to consider the effects of various mix design parameters that affect the strength gain process. Caltrans does not specify a particular concrete mix design for its paving projects, but instead requires the contractor to develop a mix design that meets certain strength requirements (performance related). The effect various mix design parameters have on the development of the maturity model's constants and corresponding strength predictions must be quantified before implementing this technology.

1.3 PROJECT OBJECTIVES

The main objective of this project was to develop guidelines for implementing concrete maturity technology, initially for use in Caltrans' paving projects. These guidelines are not intended to serve for early opening to traffic for concrete pavements within the State. This research project involved meeting these objectives by conducting a laboratory study for concrete maturity testing and included flyash-portland cement blended concrete mixtures typically used in California.

The main goals and sub-goals as identified for the PCC maturity test plan and test data analyses can be briefly summarized as follows:

1. To prove that the time-temperature maturity of concrete can be correlated to flexural strength.
2. To verify that maturity is correlated to compressive strength, for the same mix and at the same curing times.
    a. This verification allows for a comparison of the strength-maturity relationships using compressive strength vs. flexural strength relationships, and it should also provide an insight into the suitability of maturity to predict either of these strength-related parameters.
3. Evaluate the effect of mix design and curing parameters – flyash content and curing temperature in particular – on maturity measurements.
4. Compare the functioning and accuracy of the various maturity meters that are currently available, using the same set of mixtures using maturity measurements made at the same times (i.e., at the same concrete ages).
5. Evaluate and compare the performance of the two available methods of calculating maturity (Nurse-Saul vs. Arrhenius) using an identical set of mixtures and curing conditions, and assess the maturity meters that adopt these two methods of calculation.
6. Create a California Test Method (CTM) for maturity testing.
7. Include maturity requirements in the State's Special Provisions as a construction specification provided the experimental maturity test results validate the benefits of doing so.

It is important to note that the intent of this project is not to favor one method of maturity testing or interpretation of test results, nor to help select one maturity meter over another.

CHAPTER 2

CONCRETE MATURITY

2.1 CONCEPT OF CONCRETE MATURITY

Concrete is generally considered a heterogeneous but uniformly distributed hydraulic, cementitious material consisting of water, air, coarse and fine aggregate, and usually some form of admixture. The chemical reaction between the cementitious materials and water, commonly referred to as hydration, progresses over time to form the binding material and results in strength gain of the material. Hydration is an exothermic reaction; thus heat is liberated during the reaction. The hydration process therefore encompasses both strength gain and heat discharge. The simultaneous occurrence of these two phenomena during hydration can be leveraged to correlate the level of strength gain to the amount of heat generated, as depicted in Figure 1. The heat generated is estimated in terms of the measured temperature.

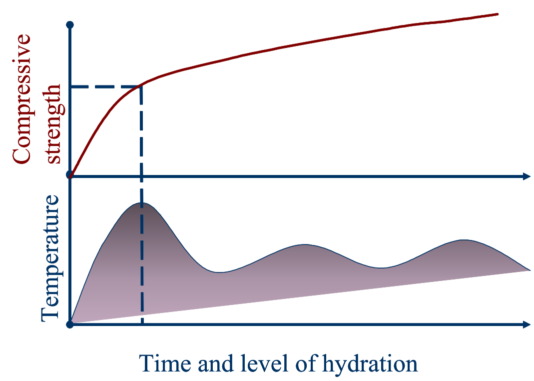


Figure 1. Maturity concept – strength gain and heat release during hydration

The early age hydration of a concrete mixture is characterized by a complex interaction of several mix design and curing condition variables. The ability to correlate strength gain to heat generated as a result of the interaction of all these factors forms the basis for concrete maturity. The heat generated is estimated from the thermal history monitored for the mixture, which is the temperature data collected over time. The extent of reaction and the rate of the hydration process, which in turn can be correlated to strength gain, are combined in the concrete maturity term. The index used to define maturity is derived from a mathematical function that integrates elapsed time and hydration temperature monitored over the time period under consideration. Maturity is mathematically the integration of the area under the time-temperature history curve plotted for a given mixture. Note that any changes to the strength gain process resulting from changes to mix design parameters (for e.g. retarding agents, water-cement ratio) or curing conditions (temperature or relative humidity) gets reflected to the area under the strength-maturity curve and therefore into the maturity index.

Although maturity indices have been implemented recently as a pointer to predict the strength of a concrete mixture, the underlying concept has been recognized and practiced for many decades. For example, higher hydration temperature conditions result in overall higher strength gains in the mixture, while lower hydration temperature conditions cause a certain retarding effect on the hydration process. These are basic applications of the fundamental maturity concept that has been qualitatively and, more recently, quantitatively known to engineers.

The concept of using the hydration temperature history to predict concrete strength gain was first introduced by Nurse (1949) and Saul (1951) who independently worked in the area of steam curing processes for fresh concrete. More recently, these concepts have been utilized and incorporated into practice. The importance of being able to relate the temperature conditions to concrete strength gain was realized as a result of a catastrophic failure of a concrete deck in Virginia in 1973. This failure caused a loss of several human lives and injuries to coworkers. An investigation into the causes of this accident revealed that the formwork was removed prematurely. The concrete had not gained adequate strength as a result of being exposed to only 4 days of curing at 45^{O}F. While the concrete industry started making progress with studies on concrete maturity to better explain the effect of curing temperature for this deck failure, a second construction failure followed in 1978, in West Virginia, also resulting in several deaths and injuries. Here, a newly placed structure had not gained enough strength to withstand the construction loads being applied to it. The investigation carried out by the National Bureau of Standards (NBS, now called the National Institute for Standards and Technology, NIST) while assisting the Occupational Safety and Health Administration with these two failures, emphasized not only the importance of temperature conditions in the concrete strength gain process, but also the need for accurately assessing the in-situ strength of the material (Carino, 2001).

The strength values obtained from companion beam or cylinder specimens cast during construction are not necessarily accurate, because the curing conditions of the field-cured structure and the associated specimens, whether cured in the lab or in the field, are not identical. This concept is depicted in Figure 2. The California Department of Transportation handles the potential difference between field-cured concrete, and laboratory-cured concrete by a factor of safety built into the strength acceptance criteria.

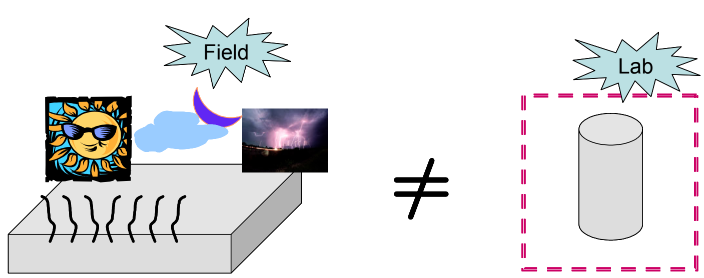


Figure 2. Field cured structures differ from laboratory (or field) cured specimens

The maturity concept that was introduced as a result of further investigations and research is illustrated in Figure 3. The time-temperature history for the samples shown in Figure 3 are drastically different, with one undergoing a longer period of curing at a lower temperature and the other undergoing a shorter period of curing at a higher temperature. This conceptual example indicates that the net heat released by each reaction process, estimated by the area under the time-temperature curve, are equal, thus resulting in similar levels of "maturity" or "aging" of the concrete mixture. The fundamental concept of maturity relies on the thesis that these two samples will have attained approximately the same strength levels as long as the samples were prepared using an identical mix design with adequate access to water for the hydration process. In other words, *"concrete of the same mixture at the same maturity has approximately the same strength, whatever combination of temperature and time go to make up that maturity"* (Saul, 1951).

Maturity does not directly measure the strength gain of a concrete mixture. Instead, it provides a parameter that indirectly indicates the strength, or a measure of the strength gain, of the mixture. The concept also does not imply that concrete should be cured at high temperatures or heated for the best overall strength gains. The traditional recommendations for curing conditions, i.e. optimum temperature and moisture levels, continue to be significant; however the time-temperature history is still a good *indicator* of the time and temperature dependent strength gain. The calculation of the maturity index, and the mathematical models to do so, are explained in Section 2.2.

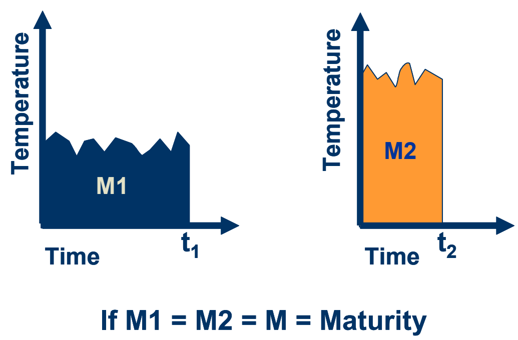


Figure 3. Equivalent concrete mixture maturities

The currently available national standard for performing maturity-related tests is ASTM C 1074-98, *Standard Practice for Estimating Concrete Strength by Maturity Method* (ASTM, 1998).

2.2 MATURITY FUNCTIONS

As discussed above, the maturity value is an index to correlate thermal history to strength gain. The current ASTM procedure provides two functions to calculate maturity, namely the Nurse-Saul function and the Arrhenius function.

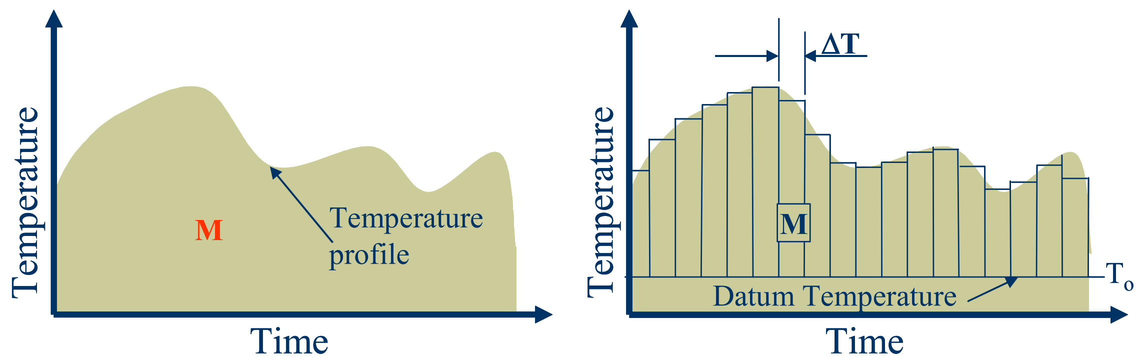
2.2.1 The Nurse-Saul function

The Nurse-Saul function calculates the maturity index known as the temperature-time factor, TTF, expressed in degC-hour. The temperature-time factor is the area under the time-temperature curve for the mixture as illustrated in Figure 4. The Nurse-Saul function is expressed as:

$$M = \sum_{0}^{t} \left(T - T_o\right) \cdot \Delta t$$

where:

M is the maturity index, temperature-time factor, degC-hour
T is the measured temperature, ^{O}C
T_o is the datum temperature, ^{O}C
Δt is the time interval between successive temperature measurements, hour



a) Time-temperature profile b) Approximating area under curve

Figure 4. Area under time-temperature curve for the temperature-time factor

This equation, in essence, accumulates the area under the curve above a standard datum temperature. In other words, the equation assumes that the hydration process taking place in the concrete mixture at all times when it is above the datum temperature level contributes to strength gain. The selection of this datum temperature level is crucial in the determination of the maturity index and also very important in physically accounting for all periods of strength gain while the concrete is hydrating. Typical datum temperature values being used in practice and quoted in literature range from $-10^{O}C$ to $+10^{O}C$ ($14^{O}F$ to $50^{O}F$).

The Nurse-Saul function is a linear maturity-accumulation function and, accordingly, assumes maturity is directly proportional to the difference in temperature between the actual temperature of the mixture and the datum temperature. In other words, if the datum temperature is $0^{O}C$, then a mixture at $40^{O}C$ will develop approximately twice the maturity as the same mixture at $20^{O}C$ for identical curing times. Note that the datum temperature is a critical value in assessing the relative strength gain of a mixture at different temperature levels.

2.2.2 The Arrhenius function

The Arrhenius equation was adopted to evaluate the rate of the hydration process, also by considering the nonlinear effects of strength gain at different temperature levels and at varying curing temperatures. The Arrhenius function considers maturity in terms of a factor called the "equivalent age", i.e., in terms of strength gain at a reference temperature. If a reference temperature of, for example, $20^{O}C$ ($68^{O}F$) is used, the equivalent age factor will give a measure of the age of the mix relative to the $20^{O}C$ curing temperature. For example, if a mixture is cured at $40^{O}C$ for 7 days, its equivalent age relative to a $20^{O}C$ curing mixture will be greater than 7 days. Similarly, if the mix is cured at $10^{O}C$, then its equivalent age relative to a $20^{O}C$ curing condition will be less than 7 days.

The equivalent age factor is expressed as:

$$M = \sum_{0}^{t} e^{\frac{-E}{R}\left[\frac{1}{T}-\frac{1}{T_r}\right]} \cdot \Delta t$$

where:

M is the maturity index equivalent age factor, hour
E is the activation energy, J/mol
R is the universal gas constant, 8.314 J/mol-k
T is the average absolute temperature of concrete in time "Δt," ^{O}Kelvin
T_r is the absolute reference temperature, ^{O}Kelvin

The activation energy, a key input to the Arrhenius equation, is indicative of the energy required to initiate the hydration reaction process. This factor accounts for the effect of temperature on strength gain and is also described as the energy barrier to be overcome by the reactants before reaching a lower energy level to initiate the reaction. This factor has a different value for each mixture, depending on the cement type, mix constituents, and mixture proportions, and should be ideally be determined through laboratory tests. However, for mixtures containing no mineral admixtures, i.e. non-blended cement mixtures, the recommended activation energy is about 40,000 Joules/mole. In the presence of admixtures that retard the reaction, the activation energy typically decreases somewhat.

Note that the Arrhenius equation accounts for varying initial curing temperatures but does not account for the "cross-over" effect, which is essentially the influence of early age temperature in long-term strength gains. This equation also allows for a non-linear (exponential) relationship between strength gain and curing temperature. In this study, however, the activation energy was not determined in the lab. For the purpose of comparison between Nurse Saul and Arrhenius methods, the activation energy value was optimized for best strength predictions.

2.3 USING MATURITY FOR PREDICTING STRENGTH

The measurements necessary to carry out maturity calculations can be obtained using commercially available maturity loggers or temperature measuring devices. The devices are relatively straightforward and convenient to use. The use of maturity to estimate concrete strength gain of in-situ concrete mixtures involves a simple procedure; however, it is one that involves both laboratory testing and field monitoring.

Laboratory Procedure: The lab procedure consists of a series of strength tests and temperature measurements to develop a mix-specific model in order to relate concrete maturity to strength gain. This process involves the following steps:

1. <u>Prepare concrete specimens and install maturity meters</u>: Prepare the required number of cylinders for standard compressive strength tests and/or beams for standard flexural strength tests. The concrete mixture proportions and constituents shall be identical to those to be used in the field project. The sizes of the specimen shall be same as those used later in the project for verification. Embed temperature sensors or maturity loggers in the required number of specimens.

2. <u>Record maturity in the concrete specimens</u>: Place specimens in the specified standard curing conditions in which maturity measurements will be made. During the curing process, record maturity from the time of casting at specified time intervals — typically 15 minutes in the initial 24 hours, 30 minutes for the next 48 hours, and every hour from then on — using maturity meters. If temperature sensors are used, calculate maturity accumulated over the hydration period.

3. <u>Perform strength tests at different ages</u>: Perform compressive strength or flexural strength tests at specified ages, e.g. 1, 3, 5, 7, 14, and 28 days if a complete maturity curve is desired. Note that the maturity values at these ages are known from Step 2. Laboratory strength tests will require the specified number of repetitions (specimens per test age) as per the test method or CTM employed.

4. Develop the strength-maturity relationship: Correlate the maturity index at each age with the lab-measured strength values to develop a strength-maturity relationship as shown in Figure 5, in this example for flexural strength in psi.

The strength-maturity relationship curve is most commonly a logarithmic function that defines concrete strength as a function of maturity. The logarithmic best-fit curve, as illustrated in Figure 5, is of the form:

*Strength = A*log(maturity) + B*
where:

A and B are the regression constants based on the test data

The strength-maturity relationship is the logarithmic best-fit curve, an example of which is shown in Figure 5.

Field Procedure: The field procedure consists of installing maturity loggers or temperature sensors in the structure being constructed and monitoring the internal hydration temperature data over time. This process involves the following steps:

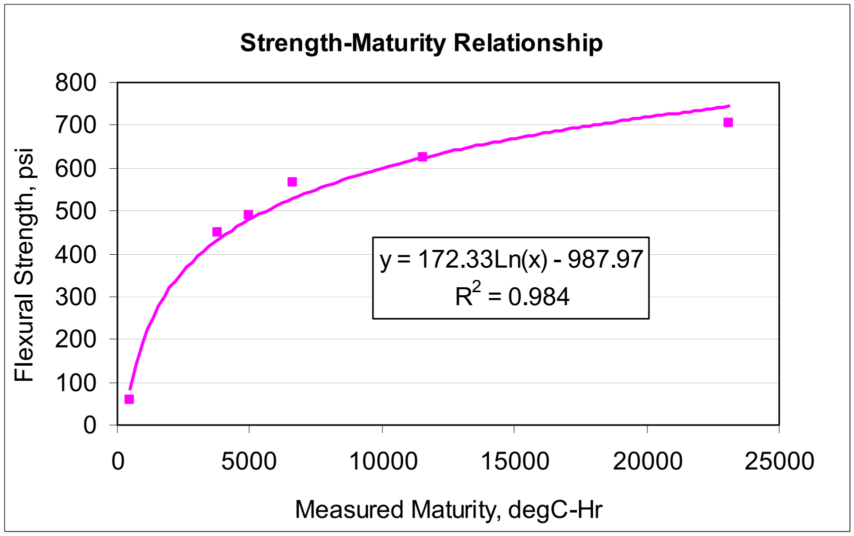


Figure 5. Strength-maturity relationship for flexural strength using the time-temperature factor as the maturity index

1. Collect field maturity data: Embed maturity sensors at critical locations in the concrete structure at the time of placement and collect maturity or time-temperature data as per field monitoring protocols. If temperature sensors are used, calculate maturity from the temperature data as a function of elapsed time.

2. Estimate in-place strength: Based on the strength-maturity relationship developed in the laboratory, calculate or predict the strength of the in-situ concrete. Alternatively, the maturity value to attain a required strength level can be read off from the strength-maturity relationship, as shown in Figure 6. The field structure may be assumed to have the required strength when the maturity recorded is equal to a value corresponding to the desired strength level.

2.4 RELEVANT STUDIES

Several agencies have already investigated the accuracy and the practicality of using maturity concepts in QC/QA applications. Based on their studies, standard test protocols and specifications have been introduced by many of these agencies for use in concrete construction projects. Two examples of these studies are briefly summarized below.

The Pennsylvania DOT conducted a very comprehensive study (Tikalasky et al., 2000) on the application of this technology for both structural members and pavements. Concrete mixtures containing supplementary cementitious materials were used in the study, involving pier, bridge deck, and pavement slab construction in four different seasons. Three different maturity loggers were evaluated in the study. The study also investigated the specific locations within the structure where maturity readings were lowest for a given age, and therefore the resulting variability in strength gain trends could be identified within the structure. Issues such as the effect of an admixture in the mix and the accuracy of different models for the strength-maturity relationship were investigated. The study resulted in a recommendation for the use of maturity, but recommends that the mixture used to develop the strength-maturity relationship should be cured in conditions as close as possible to the expected field conditions. The maturity device proposed is one with a digital phone technology for real-time monitoring of strength gain. A standard test method and specification were developed from this study.

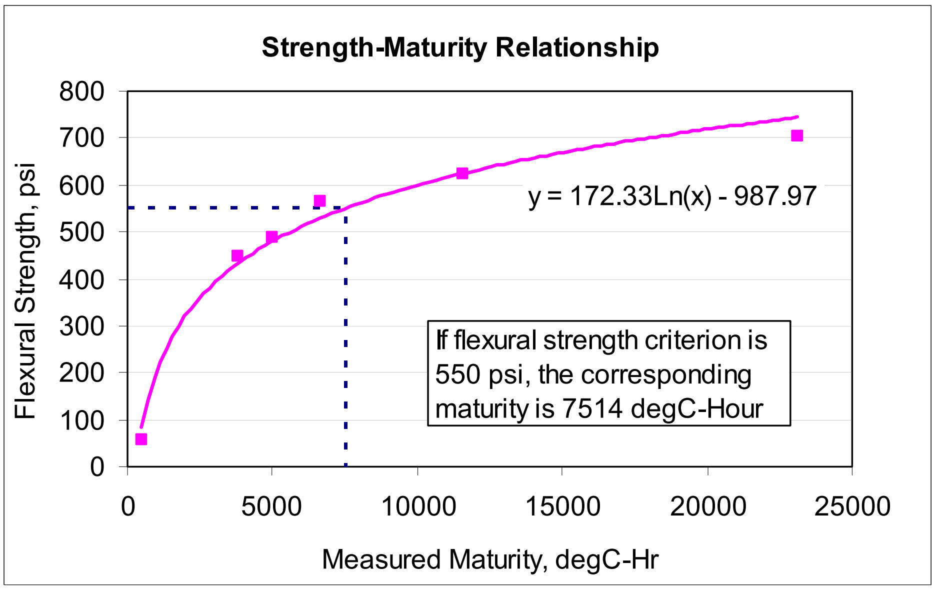


Figure 6. Reading off field measured maturity from the lab-developed strength-maturity relationship from the same mixture

In another study, the Indiana DOT (Newbolds et al, 2001) evaluated the ability of concrete maturity to predict flexural strength in conjunction with fatigue implications in concrete when the pavement is opened to traffic at relatively low levels of flexural strength. For typical concrete mixes used by the State DOT, flexural strength was found to have a strong correlation with maturity, and a maturity value calculated from Nurse-Saul function (TTF in degC-hour) was suggested that best correlated to a flexural strength criterion to open a new pavement to traffic. An evaluation of the fatigue life of the concrete at these lower flexural strength levels suggested that the pavement could in fact carry 100,000 loading cycles, as long as the flexural stress does not go above 35 percent of its flexural strength. The study strongly suggested good curing practices for proper hydration and strength gain.

2.5 ADVANTAGES AND LIMITATIONS OF USING MATURITY

There are several advantages to using concrete maturity, as listed below:

- Provides an immediate estimate of the strength development of in-situ concrete
- Strength estimates are reasonably accurate and efficient, and provides consistent strength assessments
- The method is not operator-dependent
- The method is not "specimen" dependent and fewer cylinders and beams are required to be cast and tested.
- Concrete maturity can be a cost-effective approach
- Provides the flexibility to change mix proportions to meet field conditions.

Despite the advantages recognized for this method, it is also prudent to be aware of its limitations so as to avoid a misinterpretation of maturity results. The mix design and curing conditions used for developing the strength-maturity curve should be standardized to an easy-to-use laboratory procedure, at a commonly used laboratory temperature, in the presence of moisture. The early age strength gain characteristics are crucial to the accuracy of the strength-maturity relationship developed in the laboratory. Therefore, the concrete mixes used for calibration and prediction should ideally undergo rigorous and consistent initial curing regimes under standard laboratory conditions. The maturity concept is only applicable when the mixture is hydrating properly, and therefore if there is a lack of moisture during the period of hydration, the temperature measurements will not necessarily reflect associated strength gains. Naturally, the same is true for the field structure, which must undergo proper curing and retain access to moisture throughout the critical curing period.

CHAPTER 3

DEVELOPMENT OF TEST PLAN

The experimental plan for this study was designed to address the main project goals, as listed in Chapter 1. Because the study aimed at verifying that concrete maturity can predict flexural strength, and verifying that it can predict compressive strength, both flexural and compressive strength tests were included in the plan. Different curing temperatures and mix designs were included in the test plan so that the ability of PCC maturity values to recognize and distinguish differences in strengths and rates of strength gain could be evaluated and quantified. Included in the test plan were also maturity calculations using both Nurse-Saul and Arrhenius functions for an evaluation of the effectiveness of each method. Details of the experimental test matrix and the testing plan are discussed in next section of the report.

During the conduct of the current study, the University of California, Berkeley (UCB) was also involved in a very comprehensive and detailed research project on concrete maturity involving both laboratory and field work (Mancio et al., 2004). The current study was envisioned to be a concurrent study within Translab through which relevant comparisons could be drawn with the UCB project. The UCB study used four different material sources, one of which was the source of a mix used in a paving project near Victorville, CA. This mix design used by UCB from the Victorville, CA source is identical to one of the mixes (mix 2) used in this study, details of which are discussed in the next section.

The experimental plan was developed taking into consideration both technical and practical issues. The plan was prepared during October 2003 and laboratory experiments were conducted at Translab within a minimal time schedule during the months of November and December 2003. The plan had to strategically consider factors to be able to cast specimens and perform strength tests within this time schedule, while optimizing the use of available laboratory resources and the necessary personnel for performing the requisite experimental work.

3.1 MIX DESIGN PARAMETERS IN THE TEST MATRIX

3.1.1 Number of mix designs considered in the test plan

The study was designed to evaluate the effects of changes in mix design components — specifically, flyash content and curing temperature — that affect strength gain and PCC maturity values together with the resulting strength gain curves. Two mix designs, each with the same water/cement ratio (including the flyash) resulting in approximately the same slump, were cured at four different curing temperature regimes and tested at four different ages: nominally 3, 7, 14 and 28 days. The number of design mixtures considered in the test plan adhered to the scope of the project and the time and resources available to complete the work plan in a timely manner. The mix parameters that were altered in the mix designs were within typical ranges approved by Caltrans. For this project, the parameters varied were those aspects of the mix design and curing conditions that would have the most effect on the rate of strength gain in the concrete.

The use of an air-entraining agent is required for mixtures used in concrete construction subject to freeze-thaw action, so this agent was incorporated into the two mix designs. The mix designs adopted were based on a mix used in a recent Caltrans paving project near Victorville, CA. The aggregate source in Victorville, CA was used in order to replicate a recent University of California's research project on maturity testing and enable a direct comparison of test results.

The two mixtures used, Mix 1 and Mix 2, contained Type F flyash at 15% and 25% respectively. The specimens were cured at $10^{O}C$, $23^{O}C$, and $38^{O}C$ ($50^{O}F$, $73^{O}F$, and $100^{O}F$) nominal, and at "ambient" temperature conditions for the late fall/early winter in Sacramento, California. The mixtures resulted in a total of 8 different combinations of flyash content and curing temperatures, as shown in Table 1.

Table 1. Mix design parameters

Mix ID		**Curing condition***	**Test ages****
Mix 1: 15% Flyash	Mix 1A	@ $38^{O}C$ – Immersed in water	3, 7, 14, 28 days
	Mix 1B	@ $23^{O}C$ - Immersed in water	
	Mix 1C	@ $10^{O}C$ - Immersed in water	
	Mix 1D	"Ambient" Conditions	
Mix 2: 25% Flyash	Mix 2A	@ $38^{O}C$ - Immersed in water	
	Mix 2B	@ $23^{O}C$ - Immersed in water	
	Mix 2C	@ $10^{O}C$ - Immersed in water	
	Mix 2D	"Ambient" Conditions	

* Note that the limewater bath in the $38^{O}C$ curing temperature regime was occasionally maintained at a slightly lower temperature, on average around $37^{O}C$. Note as well that the $23^{O}C$ curing temperature was closer to $24^{O}C$, on average.

** Note that Mix 2 was tested at 8 days instead of at 7 days, and Mix 1 was tested at 29 days instead of at 28 days to accommodate the non-availability of the test apparatus during the testing phase of the project. However, the associated maturity values at the time of strength tests were used in the data analysis.

The samples were moist cured throughout the test period from the time of testing. Tubs filled with limewater were used to soak the samples during the curing period after the moulds were stripped at 24 hours. The samples were initially cured with wet burlap in their respective environments over the first 24 hours, so the concrete could undergo a reasonable amount of strength gain prior to being stripped, exposed, and soaked in limewater under three of the four temperature regimes, as indicated in Table 1.

Note that the above test matrix enabled a comparison of maturity predictions for varying:

- Curing conditions (mixes 1A vs. 1B vs. 1C vs. 1D, and 2A vs. 2B vs. 2C vs. 2D)
- Flyash contents (mixes 1A vs. 2A, 1B vs. 2B, 1C vs. 2C, and 1D vs. 2D)

3.1.2 Strength tests

Traditionally, the strength-maturity curves developed for concrete mixtures have correlated concrete maturity to compressive strength. However, for paving applications, since the modulus of rupture is the Caltrans design criteria, strength-maturity models were developed based on flexural strength determined from beams tested under third point loading conditions. In addition, compressive strength tests were also performed to examine if the correlations sought with compressive strength were similar to those obtained from flexural strength, and secondarily if there is a reasonable relationship between compressive and flexural strength using typical Caltrans mix designs.

3.1.3 Ages for strength tests

Strength tests were performed at 3, 7, 14, and 28 days for each curing environment. These test ages include the time range while the concrete undergoes early-age strength gain, which is very important in defining the shape or slope of the strength gain curve. Furthermore, it also allows for strength evaluation at 28 days, which forms the basis for comparison with the design flexural strength of the concrete.

3.1.4 Repetitions

The issue of sample size and number of repetitions (samples) addresses the necessary number of specimens to be tested, at each age and for each sample. In general, repeatability and accuracy are key elements to the acceptance of any test method or specification. In addition, the accuracy of the strength determined at each age contributes significantly in defining a strength-maturity curve. The normally recommended strength parameter is the average compressive strength computed from three trials of compressive strength test samples (6” diameter x 12” cylinders).

The variability in flexural strength testing is generally higher. It was therefore recommended that the average flexural strength from four beam tests be used as a representative flexural strength value. The use of four beam specimens in lieu of three also assists in defining the precision associated with the proposed test method. One beam and one cylinder specimen from those cast were used to install maturity loggers. Note that the intent of this experimental procedure was not to assess the repeatability of the test methods.

Accordingly, the number of specimens required for each sample set, for each mix design combination and for the various curing conditions, were as follows:

Beams:

- 4 ages x (3 specimens for testing + 1 specimen for maturity readings) each age = 16 beams

Cylinders:

- 4 ages x (2 specimens for testing + 1 specimen for maturity readings) each age = 12 cylinders

3.1.5 Test schedule

A schedule for casting and testing of the concrete was prepared, based on an optimum time frame and the extent of testing capabilities currently available at Caltrans' Translab. Table 2 shows the casting and testing schedule for the entire project. Batching of the mixes were limited to no more than 2 batches of mixing per day of casting and each batch contained no more than 5 cubic feet of hydraulic concrete. Testing was performed beginning on the third week of the schedule.

Note that beam and cylinder testing was performed in reverse order of casting (in most cases), when and as required, so as to minimize project time, i.e. beams and cylinders cast first were tested for 28-day strengths while those cast last were tested for earlier age strengths in order to achieve an optimum casting and testing schedule considering total elapsed time, weekends, and holidays, etc. Table 2 depicts the casting and testing days for strength tests at all ages.

Table 2. Test schedule

Date and Day of week	Mon Day N-1 3-Nov	Tue Day 1 4-Nov	Wed Day 2 5-Nov	Thu Day 3 6-Nov	Fri Day 4 7-Nov	Sat Day 5 8-Nov	Sun Day 6 9-Nov	Mon Day 7 10-Nov	Tue Day 8 11-Nov	Wed Day 9 12-Nov	Thu Day 10 13-Nov	Fri Day 11 14-Nov	Sat Day 12 15-Nov	Sun Day 13 16-Nov
		Casting days (beams & cylinders for testing & maturity meters)												
% Fly ash - >		15%		25%				15%		25%				
Mix ID Cure		Mix 1		Mix 2				Mix 1		Mix 2				
Temp A at 38C		4b+3c		4b+3c				4b+3c		4b+3c				
Temp B at 23C		4b+3c		4b+3c				4b+3c		4b+3c				
Temp C at 10C		4b+3c		4b+3c				4b+3c		4b+3c				
Temp D Amb.		4b+3c		4b+3c				4b+3c		4b+3c				
Total cast/day		16b+12c		16b+12c				16b+12c		16b+12c				
For 3 days									NOTE: Strip on Veterans Day the 11th of November					
Temp A														
Temp B														
Temp C														
Temp D														
For 7 days														
Temp A														
Temp B														
Temp C														
Temp D														
For 14 days														
Temp A														
Temp B														
Temp C														
Temp D														
For 28 days														
Temp A														
Temp B														
Temp C														
Temp D														
Total tests/day														

Date and Day of week	Mon Day 14 17-Nov	Tue Day 15 18-Nov	Wed Day 16 19-Nov	Thu Day 17 20-Nov	Fri Day 18 21-Nov	Sat Day 19 22-Nov	Sun Day 20 23-Nov	Mon Day 21 24-Nov	Tue Day 22 25-Nov	Wed Day 23 26-Nov	Thu Day 24 27-Nov	Fri Day 25 28-Nov	Sat Day 26 29-Nov	Sun Day 27 30-Nov	Mon Day 28 1-Dec	Tue Day 29 2-Dec	Wed Day 30 3-Dec	Thu Day 31 4-Dec
% Fly ash - >	15%		15%		25%				25%									
Mix ID Cure	Mix 1		Mix 1		Mix 2				Mix 2									
Temp A at 38C	4b+3c		4b+3c		4b+3c				4b+3c									
Temp B at 23C	4b+3c		4b+3c		4b+3c				4b+3c									
Temp C at 10C	4b+3c		4b+3c		4b+3c				4b+3c									
Temp D Amb.	4b+3c		4b+3c		4b+3c				4b+3c									
Total cast/day	16b+12c		16b+12c		16b+12c				16b+12c									
				Test days (includes beams & cylinders for maturity readings)														
For 3 days				3d-M1		NOTE: Strip on Saturday the 22nd November.		3d-M2										
Temp A				4b+3c				4b+3c										
Temp B				4b+3c				4b+3c										
Temp C				4b+3c				4b+3c										
Temp D				4b+3c				4b+3c										
For 7 days										7d-M1						7d-M2		
Temp A										4b+3c						4b+3c		
Temp B										4b+3c						4b+3c		
Temp C										4b+3c						4b+3c		
Temp D										4b+3c						4b+3c		
For 14 days								14d-M1		14d-M2								
Temp A								4b+3c		4b+3c								
Temp B								4b+3c		4b+3c								
Temp C								4b+3c		4b+3c								
Temp D								4b+3c		4b+3c								
For 28 days																28d-M1		28d-M2
Temp A																4b+3c		4b+3c
Temp B																4b+3c		4b+3c
Temp C																4b+3c		4b+3c
Temp D																4b+3c		4b+3c
Total tests/day				12b+8c*				24b+16c*		24b+16c*						24b+16c*		12b+8c*

* NOTE: Beams and cylinders for testing totals, above, do not include maturity "dummies".

CHAPTER 4

DATA ANALYSIS AND ANALYSIS OF RESULTS

4.1 SCOPE OF DATA ANALYSIS

The data collected were of two main categories: strength data and time-temperature data. Strength data included both flexural and compressive strengths values determined from laboratory testing of samples in compliance with CTM 523 and CTM 521 respectively. Strength tests were performed at 3, 7, 14, and 28 days as per the designed experimental test plan shown in Table 2. For the two mixes used in the study, the time-temperature history was monitored under each curing condition for each test age. Temperatures were recorded at 15-minute intervals from the time of casting to the time of testing.

The time-temperature history was used to calculate maturity indices using both the Nurse-Saul and Arrhenius functions. For the samples that were cured at 23^{O}C, for both mix 1 and mix 2, the strength data were correlated to the maturity values determined in order to develop strength-maturity models for each specific sample. The model (developed using the 23^{O}C sample) was used to predict the strength of the samples cured at the nominal 10^{O}C and 38^{O}C temperature conditions, respectively, based on their maturity values for all test ages. The predicted strength values were then compared against the actual strength test results to assess the quality of prediction and the associated errors.

In the discussion of the results in this chapter, please note that consistent terminologies are used to refer to specific aspects of the test matrix and experimental work. The word "mix" refers to one of the two mix designs, mix 1 and mix 2, which vary only by their flyash contents. The word "sample" refers to the set of specimens associated with each mix-curing condition combination, i.e. the experimental design contained 8 sample sets (2 mixes cured at 4 curing temperatures). The word "specimen" refers to each individual cylinder or beam in each sample that was cast and tested and/or monitored for temperature measurements. In other words, each sample was tested for its flexural strength using four specimens and for its compressive strength using three specimens.

4.2 ANALYSIS OF STRENGTH DATA

Compressive strength tests were performed at 3, 7, 14, and 28 days using three repetitions (including the specimen with the maturity gage). The average compressive strength was used for each testing age. The averages computed were all within 10% of the compressive strength of any individual specimen, for each sample. Flexural strength tests were performed at 3, 7, 14, and 28 days using four repetitions, including the specimen that contained the maturity gage. The average flexural strength was used for each testing age. The averages computed were all within 10% of the flexural strength of any individual sample, for each sample. The average flexural and compressive strengths for mix 1 are summarized in Table 3 and Table 4 respectively, while the average flexural and compressive strength for mix 2 are summarized in Table 5 and Table 6 respectively.

Table 3. Measured flexural strengths for mix 1 with 15% flyash, psi

Curing temperature	3 day (psi)	7 day (psi)	14 day (psi)	29 day (psi)
$38^{O}C$ - Mix 1	467	577	587	660
$23^{O}C$ - Mix 1	520	583	603	687
Ambient - Mix 1	295	450	500	460
$10^{O}C$ - Mix 1	470	540	613	623

Table 4. Measured compressive strength for mix 1 with 15% flyash, psi

Curing temperature	3 day (psi)	7 day (psi)	14 day (psi)	29 day (psi)
$38^{O}C$ - Mix 1	3,500	4,209	4,564	5,277
$23^{O}C$ - Mix 1	3,401	4,075	4,538	5,008
Ambient - Mix 1	3,234	4,027	4,015	4,892
$10^{O}C$ - Mix 1	2,928	3,847	4,883	4,509

Table 5. Measured flexural strength for mix 2 with 25% flyash, psi

Curing temperature	3 day (psi)	8 day (psi)	14 day (psi)	28 day (psi)
$38^{O}C$ - Mix 1	403	567	733	760
$23^{O}C$ - Mix 1	487	567	623	703
Ambient - Mix 1	433	527	477	627
$10^{O}C$ - Mix 1	397	520	580	657

Table 6. Measured compressive strength for mix 2 with 25% flyash, psi

Curing temperature	3 day (psi)	8 day (psi)	14 day (psi)	28 day (psi)
$38^{O}C$ - Mix 1	3,051	3,693	5,291	5,056
$23^{O}C$ - Mix 1	3,258	4,296	4,670	5,540
Ambient - Mix 1	2,014	3,631	3,758	4,976
$10^{O}C$ - Mix 1	2,566	4,154	4,706	5,511

Note that mix 2 was tested at 8 days instead of at 7 days, and mix 1 was tested at 29 days instead of at 28 days to accommodate the non-availability of the test apparatus during the testing phase of the project. However, the associated maturity values at the time of strength tests (both compressive and flexural) were used in the data analyses. Appendix B contains the strength data for all mixes for each curing condition.

The data in Table 3 through Table 6 were first assessed for their quality. Trends in strength gain over time were observed for all samples. The data were further analyzed to compare strength gain over time for mixes 1 and 2 at the different curing temperatures. Strength data that appeared to be erroneous were first identified and eliminated from the analysis. For instance, if the strength data indicated a drop in strength as time progressed, it was evident that the strength gain data was inaccurate. In addition, strength values at 3 days for both mixes 1 and 2 cured at 38^{O}C nominal are below the respective strength values for samples cured at 23^{O}C or laboratory conditions, which is contradictory to what was expected. Reasons for low strengths are hypothesized in Section 4.3.1 of this report. Such values appear shaded in Table 3 through Table 6.

Flexural and compressive strength gain data for mix 1 were plotted against time as shown in Figure 7 and Figure 8 respectively. Similarly, flexural and compressive strength gain data for mix 2 were plotted against time as shown in Figure 9 and Figure 10 respectively. Note that those strength values that are considered erroneous or doubtful are represented as enlarged points on the graphs shown. Also note that the "ambient" (i.e. the mix stored on Translab's dock) averaged about 15^{O}C, although some specimens probably averaged a higher or lower temperature, depending on the date of casting and the actual ambient conditions that prevailed at the time.

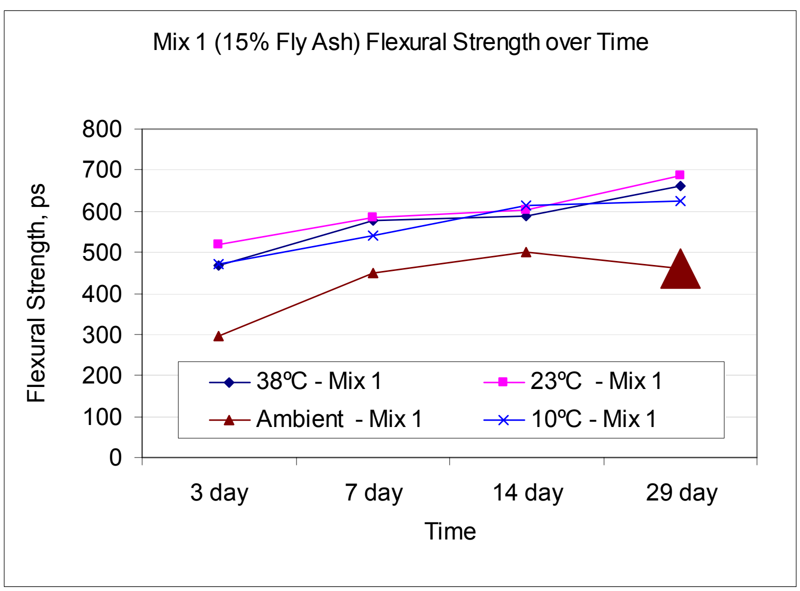


Figure 7. Flexural strength gain for mix 1 under different curing temperatures

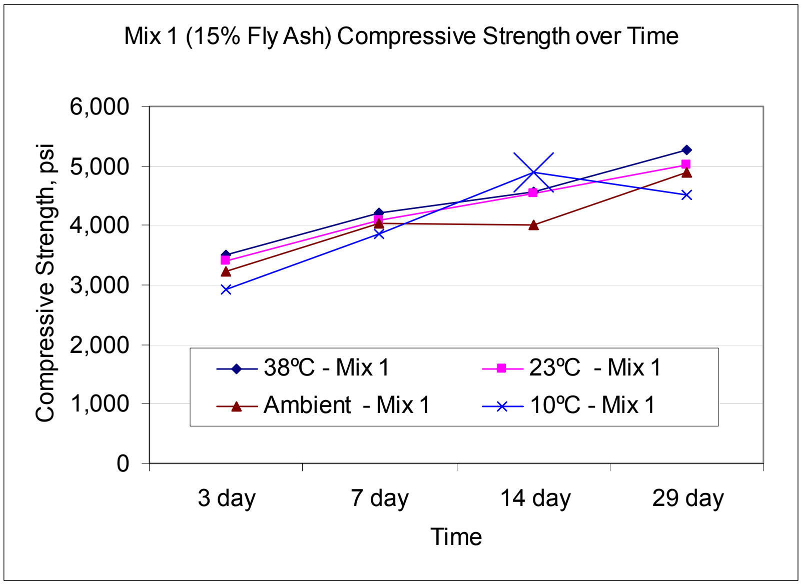


Figure 8. Compressive strength gain for mix 1 under different curing temperatures

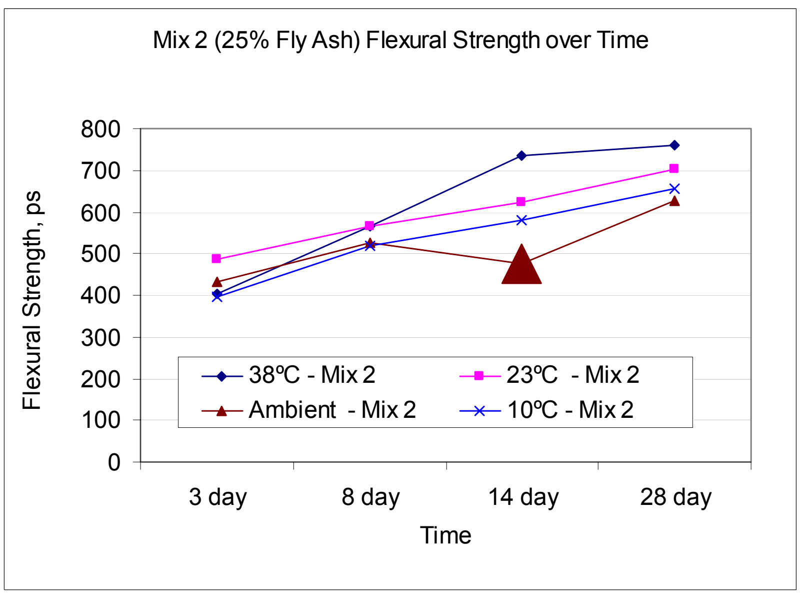


Figure 9. Flexural strength gain for mix 2 under different curing temperatures

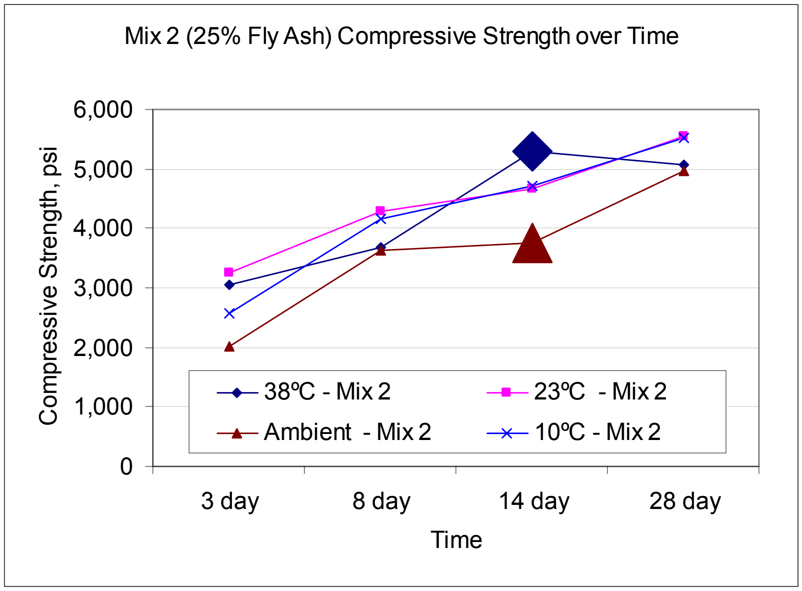
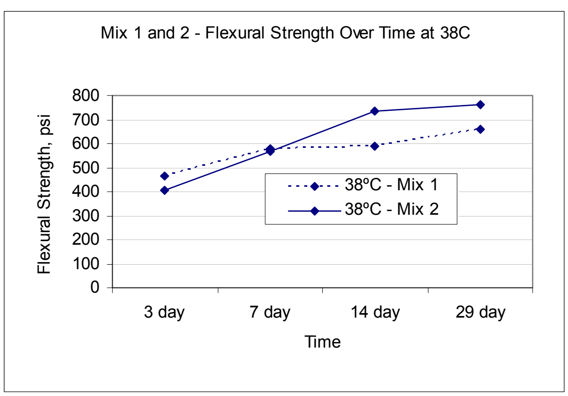
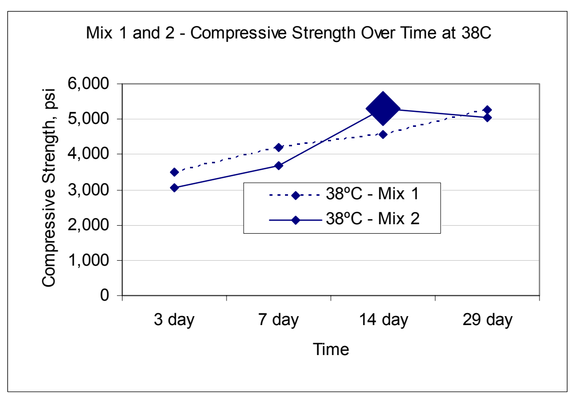


Figure 10. Compressive strength gain for mix 2 under different curing temperatures

Mixes 1 and 2 had flyash contents of 15% and 25%, respectively, at approximately the same water/cement ratios (counting flyash as part of the "cement"). Accordingly, a comparison of the strength values between the two mixes should indicate a higher rate of strength gain for mix 1 than mix 2 because of the lower flyash content in mix 1. However, the long-term strengths should be nearly the same, or possibly even higher for mix 2. For the most part, strength data verified this supposition, as shown in Figure 11, Figure 12, Figure 13, and Figure 14 for mixes cured at 38^{O}C, 23^{O}C, in ambient conditions, and at 10^{O}C, respectively.

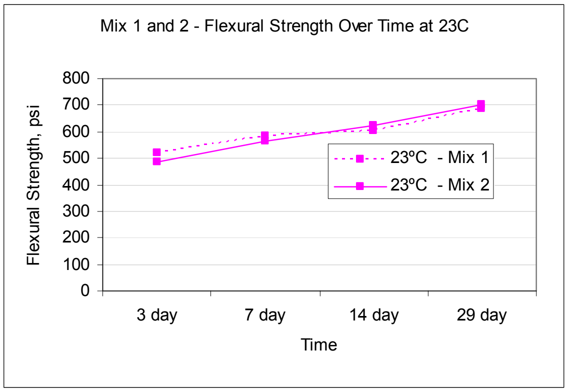


a) Flexural strength

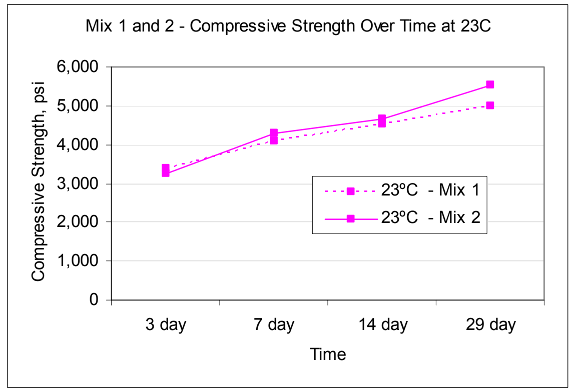


b) Compressive strength

Figure 11. Strength gain for mixes 1 and 2 cured at 38^{O}C

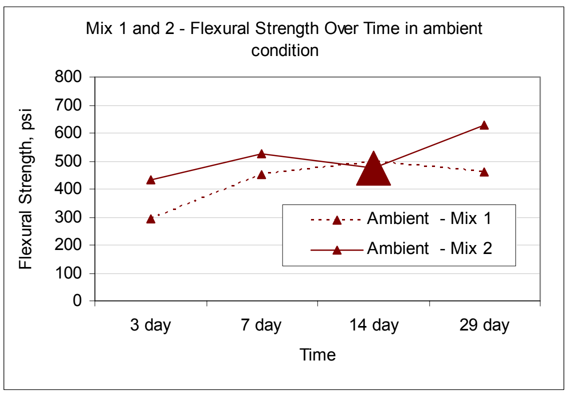


a) Flexural strength

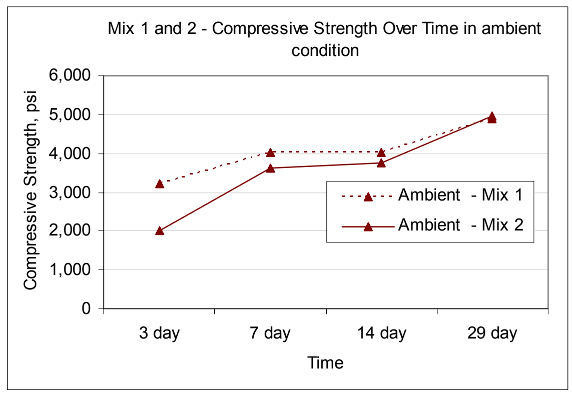


b) Compressive strength

Figure 12. Strength gain for mixes 1 and 2 cured at $23^{O}C$

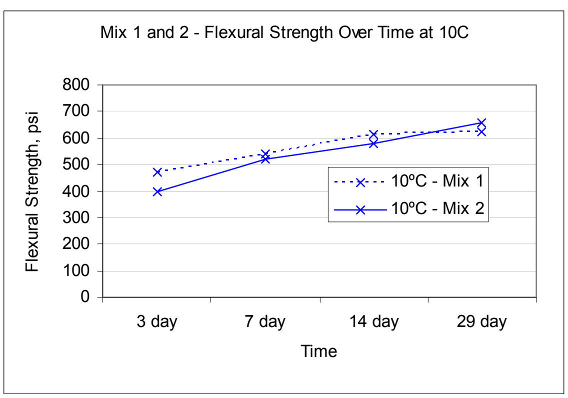


a) Flexural strength

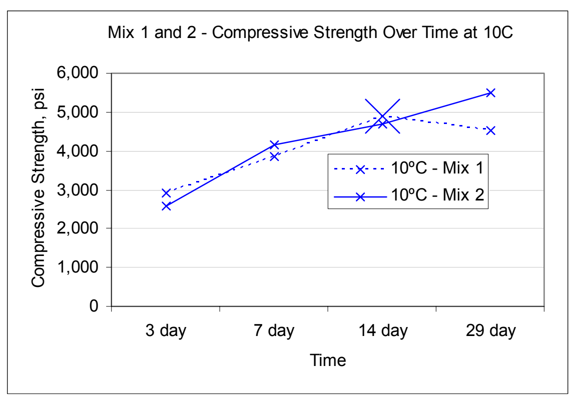


b) Compressive strength

Figure 13. Strength gain for mixes 1 and 2 cured under ambient conditions



a) Flexural strength



b) Compressive strength

Figure 14. Strength gain for mixes 1 and 2 cured at $10^{O}C$

4.3 ANALYSIS OF MATURITY DATA

Maturity indices were computed using the time-temperature history data for the 8 sample sets using both the Nurse-Saul and Arrhenius equations. Note that temperature data were available for the entire period of curing at 15-minute intervals. The maturity index computed at each time interval using the Nurse-Saul method was the *temperature-time factor* expressed in *deg C-hour*, while the maturity index computed using the Arrhenius equation was the *equivalent age* expressed in *hours*.

In the initial maturity analyses, strength-maturity relationships were developed for each sample, for both compressive and flexural strengths using the Nurse-Saul equation. A preliminary analysis was performed to evaluate how the strength-maturity relationships compared against each other. In this analysis, the datum temperature, which is a key input to the Nurse-Saul equation, ranged from -10^{O}C to +10^{O}C at 2.5^{O}C intervals. It was noted that a distinct relationship existed for each curing condition. However, when the data for all curing conditions were combined, the resulting relationships had a reasonably good statistical basis to state that the strength-maturity values belonged to the same mixture, even when cured under different temperature regimes. It was, however, noted that the maturity value to some extent depends on the curing regime, and that the optimum datum temperature value was on the low side of the -10^{O}C to 0^{O}C range, as shown in Table 7.

Table 7. R-squared of the strength-maturity relationships for mix 1 and 2 compressive and flexural strength for varying datum temperature values

(Includes data for all curing temperatures)

Datum Temperature, deg C (deg F)	Flexural Strength		Compressive Strength	
	Mix 1 (15% flyash)	Mix 2 (25% fly ash)	Mix 1 (15% flyash)	Mix 2 (25% fly ash)
-10^{O}C (14^{O}F)	63.3	89.5	95.3	77
-7.5^{O}C (18.5^{O}F)	62.4	89	94.9	75.2
-5.0^{O}C (23^{O}F)	61.2	88.2	94.3	72.9
-2.5^{O}C (-27.5^{O}F)	59.5	86.9	93.5	69.9
0^{O}C (32^{O}F)	56.9	84.8	92.3	65.8
2.5^{O}C (36.5^{O}F)	53.1	81.4	90.4	60.1
5.0^{O}C (41^{O}F)	47.1	75.5	87.4	51.7
7.5^{O}C (45.5^{O}F)	36.3	64.3	82.2	38.2
10^{O}C (50^{O}F)	11.2	32.5	69.8	10.4

Furthermore, the data also showed evidence of the optimum datum temperature being dependent on the curing temperature. This initiated an analysis of the data to establish the optimum datum temperature to utilize in the Nurse-Saul equation, i.e. the datum temperature that best represented a regression analysis of all the data. The analysis was then extended to maturity predictions using the Arrhenius equation to verify the most optimal value for the activation energy, which as mentioned previously is a key input to the Arrhenius equation. It is to be recognized that, as with maturity curves, the selection of the optimum datum temperature and activation energy values are also specific to the two mixes considered in the experimental study. Details of this analysis are discussed in Sections 4.4 and 4.5 for the time-temperature (Nurse-Saul), and equivalent age (Arrhenius) functions, respectively.

4.3.1 Analysis assumptions

It was noted that the strength values were erratic in the case of samples cured in ambient conditions on Translab's dock (see Table 3 through Table 6). There were questions raised regarding the curing conditions of these samples. As discussed earlier, there were similar issues with the initial curing conditions of the samples cured at 38^{O}C that were considered in the subsequent data analyses. The nominal 38^{O}C beam and cylinder specimens were wet cured under soaked burlap cloth soon after casting; however, the specimens were found to be in a very dry condition at the end of the 24-hour period, after which they were removed from the forms and soaked in limewater. Accordingly, in the analysis process the following assumptions were made:

- Data from the specimens cured in the ambient conditions indicated that they underwent poor curing and therefore the strength gain values, in all likelihood, were not indicative of the temperatures recorded from the devices in all instances.
- The specimens cured at the 38^{O}C nominal temperature conditions underwent poor curing during the initial 24-hour period and therefore were unrepresentative of the actual 3-day strength values characteristics of the mix at that curing temperature. However, since the samples were immersed in water thereafter (@ approx. 36-38^{O}C), the specimens were able to gain sufficient strength to follow the typical regression curves at all later ages.

4.4 ANALYSIS USING THE NURSE-SAUL METHOD

Data analysis using the Nurse-Saul method initially focused on selecting the optimum datum temperature value. For this purpose, the concrete cured at 23^{O}C was used as a control to develop a laboratory-based, room temperature strength-maturity relationship. Based on this relationship, the strengths of the samples cured at 10^{O}C and 38^{O}C nominal were predicted. The predicted strengths were then compared to the actual strengths measured for the two samples to estimate the deviation. Note that separate strength-maturity relationships were developed for mix 1 – flexural strength, mix 2 – flexural strength, mix 1 – compressive strength, and mix 2 – compressive strength. Comparisons between the actual and predicted strength values were made using the corresponding curves and models.

The procedure used in the selection of the effective datum temperature for the Nurse-Saul equation was carried out in the following manner:

1. The feasible values for the datum temperature were chosen to be: $0^{O}C$, $-5^{O}C$, and $-10^{O}C$.
2. For each datum temperature, the following analysis was done:
    i. A logarithmic strength-maturity relationship was developed for the mix 1 control sample (15% flyash laboratory cured at $23^{O}C$) by correlating the compressive strengths for the sample to their corresponding maturity values (the temperature-time factor). This is depicted in Figure 15.

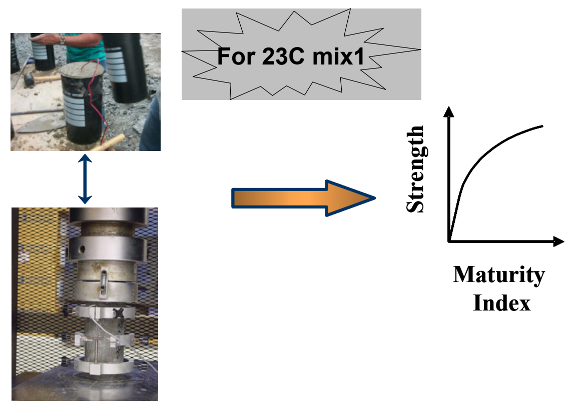


Figure 15. Establish the strength-maturity relationship for the $23^{O}C$ mix

    ii. Maturity data for the mix 1 – $10^{O}C$ sample at 3 days, 7 days, 14 days, and 28 days were extracted. Based on these maturity values and using the strength-maturity relationship developed for mix 1 in step i, above, the strengths of the samples at the given ages were predicted (i.e. they were read off the developed strength-maturity curve). This is depicted in Figure 16.

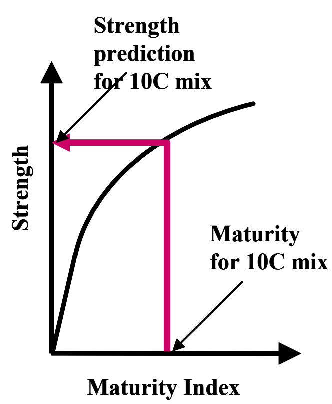


Figure 16. Predict strengths for samples cast with mix 1 and cured at $10^{O}C$

    iii. The errors in prediction were computed by comparing the predicted strengths against the actual (measured) strengths.
    iv. Repeat steps ii and iii for the nominal $38^{O}C$ mix.

v. Repeat steps i through iv for mix 1 flexural strength, mix 2 compressive strength, and mix 2 flexural strength.

Based on the above analyses, and considering predictions for both mix 1 and mix 2 at low and high temperatures, a datum temperature of -10^{O}C (+14^{O}F) was considered to be the most appropriate for use for both of the two mixes used in this study. The details of these analyses are included in Appendix C.

4.4.1 Flexural strength predictions

The flexural strength-maturity relationships developed for mix 1 and mix 2 using the samples cured at 23^{O}C are shown in Figure 17 and Figure 18, respectively. The plots also show the data obtained for the 10^{O}C and 38^{O}C mixtures. The flexural strength predictions and the associated errors for mixes 1 and 2 cured at 10^{O}C are listed in Table 8, while the corresponding data for samples cured at 38^{O}C are shown in Table 9. Note that negative errors correspond to ***underpredicted*** strength values, while positive errors correspond to *overpredicted* strength values. The negative errors are on the conservative side, especially for the 14-day and 28-day strength values, which coincide with typical times and strength gain levels required for opening the pavement to traffic. The typical time for opening the pavement to traffic is about 10 days after construction, after requisite strength levels are achieved.

Also, please note that the 3-day flexural strengths are overpredicted for the samples cured at nominal 38^{O}C for both mix 1 and mix 2. As discussed in Section 4.2 and 4.3, above, there was a fundamental problem in the 3-day strength data obtained from the 38^{O}C curing conditions for both mixes 1 and 2, as the measured strengths are higher for the lower temperature curing conditions. These errors in prediction, although high, were disregarded because the actual data against which the prediction is being compared was questionable and unreliable. Moreover, the strength values that are of significance to pavement design are attained at relatively later ages.

Table 8. Flexural strength predictions for mix 1 and mix 2 samples cured at 10^{O}C using the Nurse-Saul function for maturity prediction

Age	Mix 1 flexural strength, psi			Mix 2 flexural strength, psi		
	Predicted	Actual	Error	Predicted	Actual	Error
3 day	483	470	2.7%	431	397	8.0%
7 day	542	540	0.3%	523	520	0.6%
14 day	587	613	-4.6%	579	580	-0.1%
28 day	637	623	2.2%	643	657	-2.1%

Table 9. Flexural strength predictions for mix 1 and mix 2 samples cured at 38^{O}C using the Nurse-Saul function for maturity prediction

Age	Mix 1 flexural strength, psi			Mix 2 flexural strength, psi		
	Predicted	Actual	Error	Predicted	Actual	Error
3 day	541	467	13.7%	520	403	22.4%
7 day	606	577	4.9%	605	567	6.4%
14 day	645	587	9.0%	669	733	-9.7%
28 day	695	660	5.1%	724	760	-5.0%

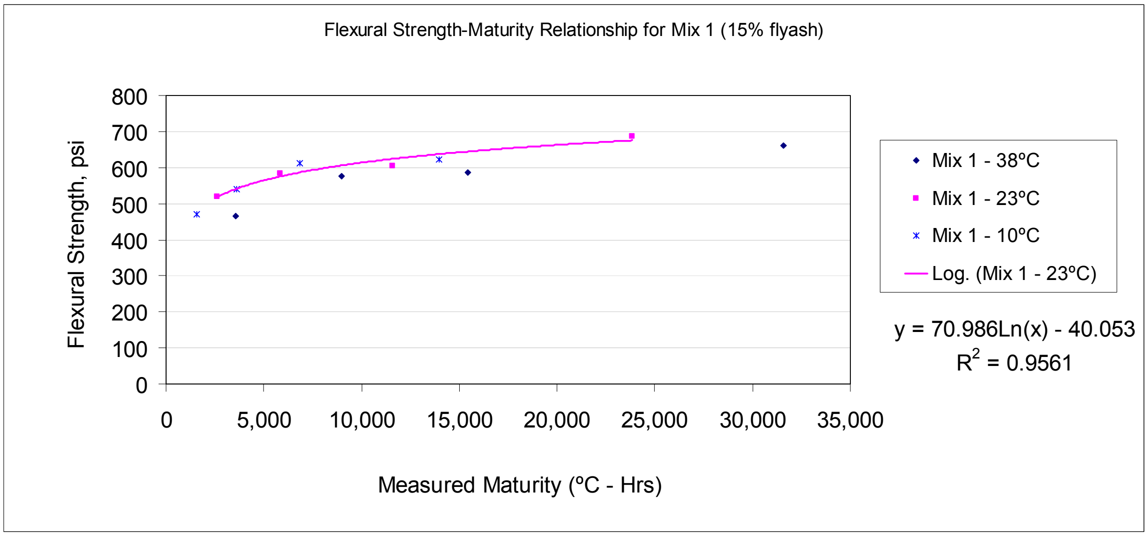


Figure 17. Flexural strength-maturity (Nurse-Saul) model for mix 1 at 23^{O}C

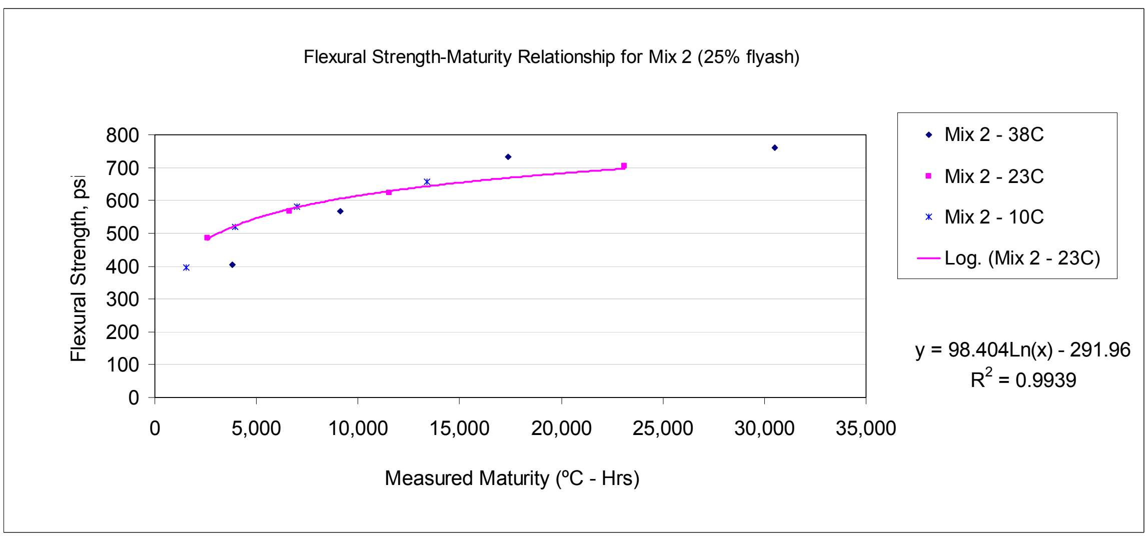


Figure 18. Flexural strength-maturity (Nurse-Saul) model for mix 2 at 23^{O}C

4.4.2 Compressive strength predictions

The compressive strength-maturity relationships developed for mix 1 and mix 2 using the samples cured at 23^{O}C are shown in Figure 19 and Figure 20, respectively. The plots also show data obtained for the 10^{O}C and 38^{O}C mixtures. The compressive strength predictions and the associated errors for mix 1 and mix 2 cured at 10^{O}C are shown in Table 10. The corresponding data for the samples cured at 38^{O}C are shown in Table 11. Since all error values are below 10%, they can be considered to be reasonable predictions.

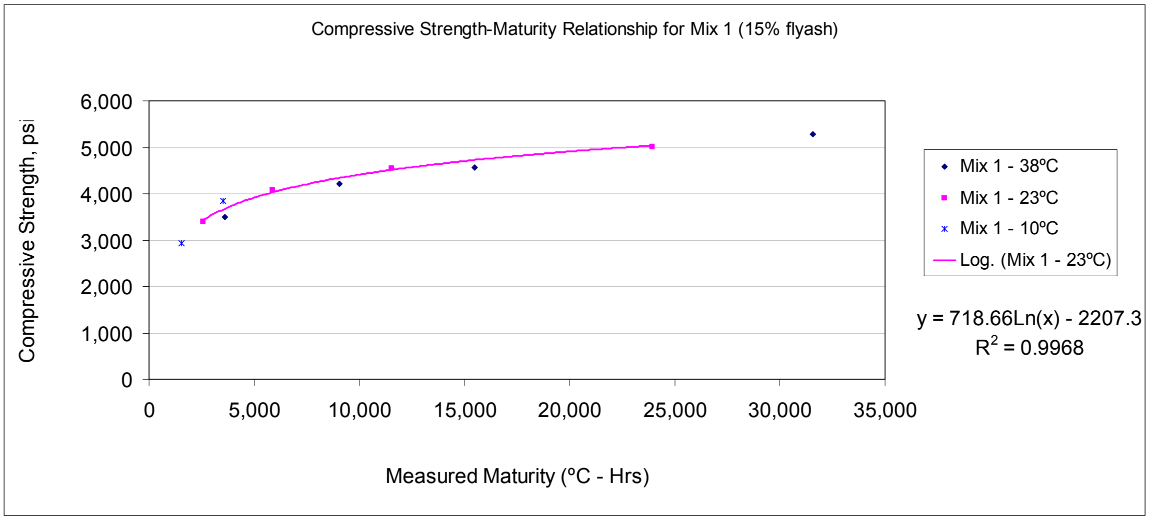


Figure 19. Compressive strength-maturity (Nurse-Saul) model for mix 1 at 23^{O}C

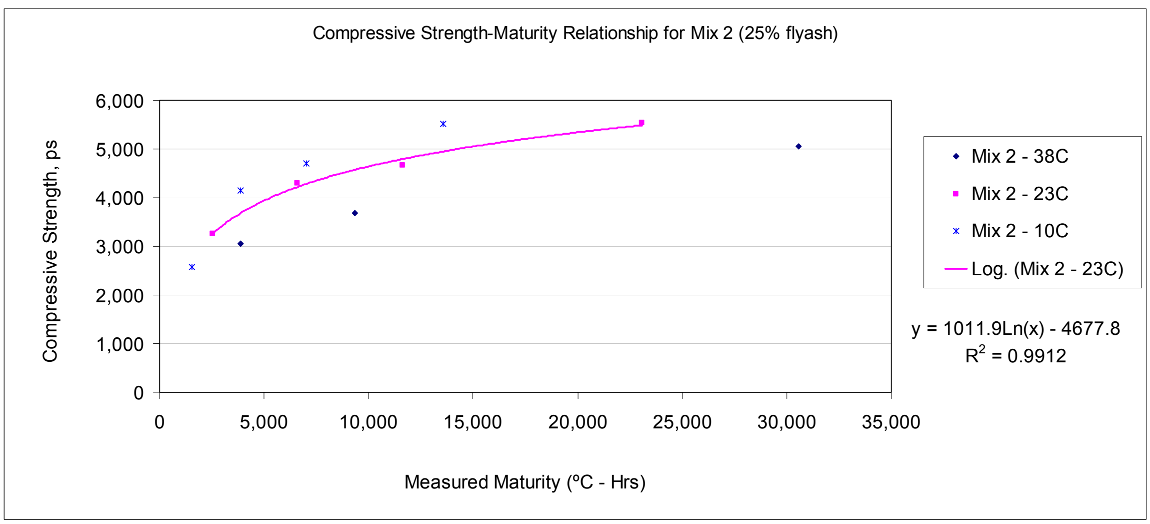


Figure 20. Compressive strength-maturity (Nurse-Saul) model for mix 2 at 23^{O}C

Table 10. Compressive strength predictions for mix 1 and mix 2 samples cured at $10^{O}C$ using Nurse-Saul function for maturity prediction

Age	Mix 1 compressive strength, psi			Mix 2 compressive strength, psi		
	Predicted	Actual	Error	Predicted	Actual	Error
3 day	3,077	2,928	4.9%	2,749	2,566	6.7%
7 day	3,661	3,847	-5.1%	3,686	4,154	-12.7%
14 day	4,156	-	-	4,282	4,706	-9.9%
28 day	4,648	-	-	4,950	5,511	-11.3%

Table 11. Compressive strength predictions for mix 1 and mix 2 samples cured at $38^{O}C$ using Nurse-Saul function for maturity prediction

Age	Mix 1 compressive strength, psi			Mix 2 compressive strength, psi		
	Predicted	Actual	Error	Predicted	Actual	Error
3 day	3,675	3,500	4.8%	3,683	3,051	17.2%
7 day	4,340	4,209	3.0%	4,572	3,693	19.2%
14 day	4,725	4,564	3.4%	5,205	-	-
28 day	5,238	5,277	-0.7%	5,773	5,056	12.4%

4.5 ANALYSIS USING THE ARRHENIUS METHOD

The activation energy is a key input to the Arrhenius equation to compute the equivalent age of the concrete mixture. Although ASTM recommends a standard activation energy value for all mixtures being evaluated using maturity concepts, it is to be recognized that for accurate predictions, the activation energy must be determined in the lab for each specific mixture. The activation energy was not calculated at Translab for these mixes. However, for similar mixes being evaluated at the University of California at Berkeley, the activation energy was determined to be 13,000 J/mole. This project was conducted in parallel, and similar to the analysis performed for Nurse-Saul method an analysis was performed using the equivalent age data to establish the optimum activation energy for these mixes based on a regression of all test data. The optimum activation energy value was thus determined to be approximately 30,000 joules/mole. Appendix D contains data that supports the choice of this activation energy value.

4.5.1 Flexural strength predictions

The flexural strength-maturity relationships developed for mix 1 and mix 2 using the samples cured at $23^{O}C$ are shown in Figure 21 and Figure 22, respectively. The maturity index used here is the equivalent age factor calculated using an activation energy value of 30,000 Joules/mole. The figures also show data points for the $10^{O}C$ and $38^{O}C$ mixes, providing a visual sense for their quality of prediction. It should be noted that this activation energy also is in line with those mentioned in the literature.

The flexural strength predictions and the associated errors for mix 1 and mix 2 cured at $10^{O}C$ are shown in Table 12. The corresponding data for samples cured at $38^{O}C$ are shown in Table 13.

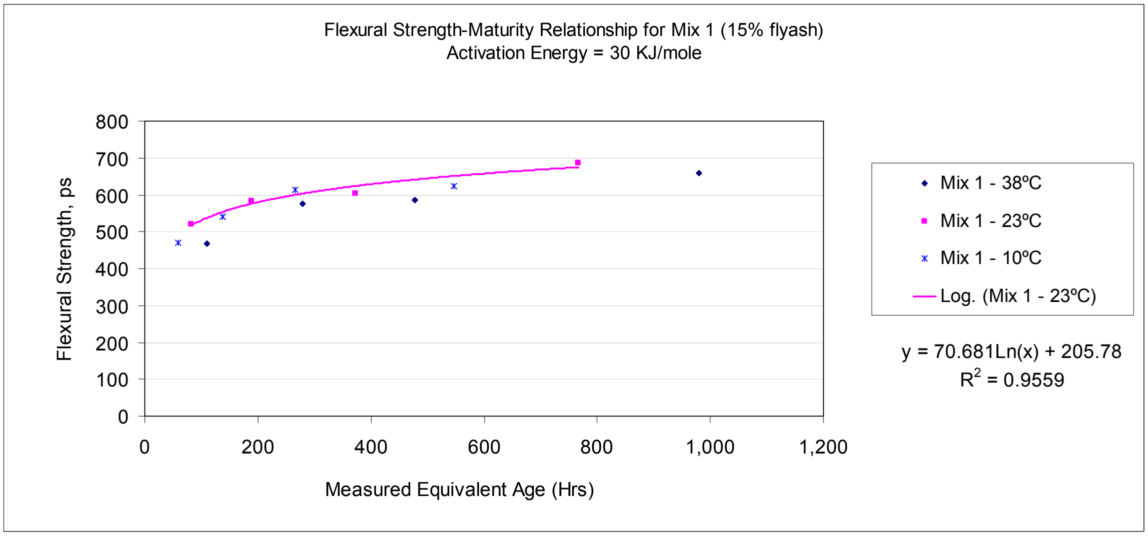


Figure 21. Flexural strength-maturity (Arrhenius) relationship for mix 1 at $23^{O}C$

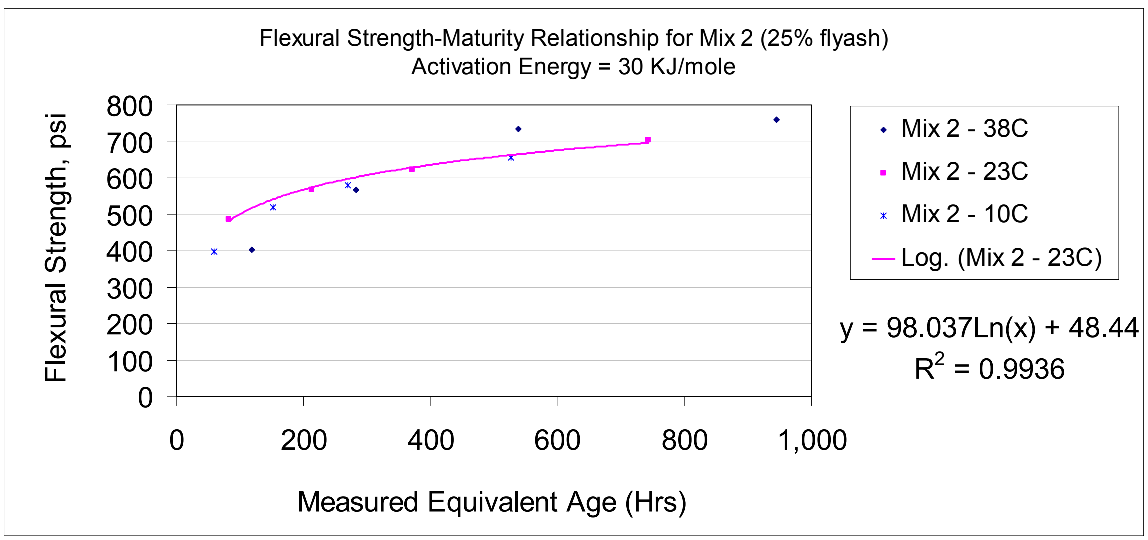


Figure 22. Flexural strength-maturity (Arrhenius) relationship for mix 2 at $23^{O}C$

4.5.2 Compressive strength predictions

The compressive strength-maturity relationship developed using the equivalent age function for mixes 1 and 2 for the samples cured at $23^{O}C$ are shown in Figure 23 and Figure 24, respectively. Again, the activation energy value used in the calculation of the

maturity index was 30,000 joules/mole. Based on the models developed, the compressive strengths were predicted for the samples cured at 10^{O}C and compared against their actual corresponding strengths measured in the laboratory. The resulting errors and a summary of these predictions are shown in Table 14. The same procedure was repeated for the samples cured at 38^{O}C and the corresponding numbers are shown in
Table 15. These tables indicate that the strength predictions are reasonably close to the corresponding (measured) strength values.

Table 12. Flexural strength predictions for mix 1 and mix 2 samples cured at 10^{O}C using Arrhenius function for maturity prediction

Age	Mix 1 flexural strength, psi			Mix 2 flexural strength, psi		
	Predicted	Actual	Error	Predicted	Actual	Error
3 day	495	470	5.2%	448	397	12.9%
7 day	554	540	2.5%	542	520	4.2%
14 day	600	613	-2.1%	597	580	3.0%
28 day	651	623	4.5%	663	657	0.9%

Table 13. Flexural strength predictions for mix 1 and mix 2 samples cured at 38^{O}C using Arrhenius function for maturity prediction

Age	Mix 1 flexural strength, psi			Mix 2 flexural strength, psi		
	Predicted	Actual	Error	Predicted	Actual	Error
3 day	538	467	15.4%	517	403	28.2%
7 day	604	577	4.7%	602	567	6.2%
14 day	642	587	9.4%	665	733	-9.3%
28 day	693	660	4.9%	720	760	-5.2%

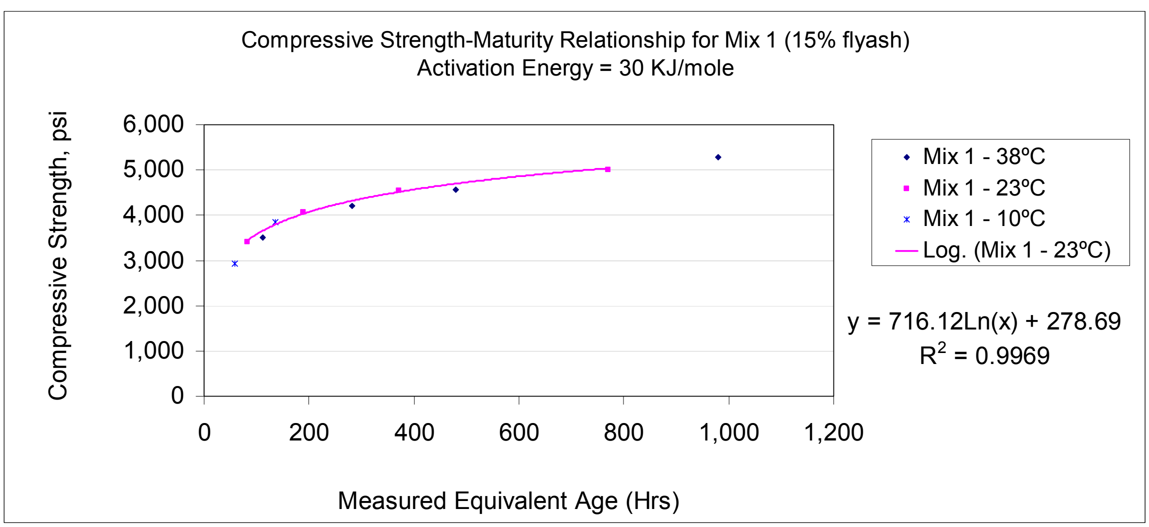


Figure 23. Compressive strength-maturity (Arrhenius) relationship for mix 1 at 23^{O}C

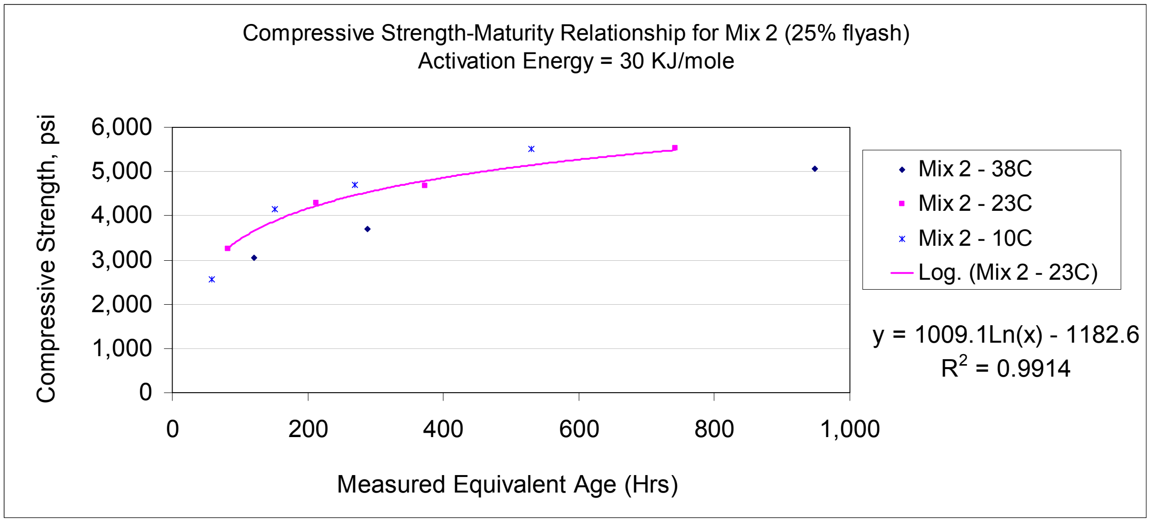


Figure 24. Compressive strength-maturity (Arrhenius) relationship for mix 2 at 23^{O}C

Table 14. Compressive strength predictions for mix 1 and mix 2 samples cured at 10^{O}C using the Arrhenius function for maturity

Age	Mix 1 compressive strength, psi			Mix 2 compressive strength, psi		
	Predicted	Actual	Error	Predicted	Actual	Error
3 day	3,077	2,928	4.9%	2,749	2,566	6.7%
7 day	3,661	3,847	-5.1%	3,686	4,154	-12.7%
14 day	4,156	-	-	4,282	4,706	-9.9%
28 day	4,648	-	-	4,950	5,511	-11.3%

Table 15. Compressive strength predictions for mix 1 and mix 2 samples cured at 38^{O}C using Arrhenius function for maturity

Age	Mix 1 compressive strength, psi			Mix 2 compressive strength, psi		
	Predicted	Actual	Error	Predicted	Actual	Error
3 day	3,199	2,928	9.3%	2,925	2,566	14.0%
7 day	3,792	3,847	-1.4%	3,886	4,154	-6.5%
14 day	4,287	-	-	4,465	4,706	-5.1%
28 day	4,792	-	-	5,148	5,511	-6.6%

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 SUMMARY

The current study was undertaken in an effort to introduce and develop supporting data as to whether to implement concrete maturity in Caltrans. Concrete maturity is a widely used technique, generally employed to evaluate the in-situ compressive strength of concrete by monitoring its temperature throughout the curing period. The ability to predict in-situ strengths could assist the Department in making decisions about appropriate times for opening pavements to traffic, sawing joints, and/or formwork removal in concrete structures. Although concrete maturity has been researched for over five decades, it has only been considered to be a viable approach recently, primarily due to improved data collection using electronic devices.

The maturity index, which is the parameter that can be correlated to strength gain in a concrete mixture, is determined from the time-temperature history of the mixture monitored from the time it is cast. The current ASTM standard for maturity testing, ASTM C 1074, recommends two maturity functions, namely the Nurse-Saul and Arrhenius equations, to determine the maturity index. The index determined based on the former function is the temperature-time factor (deg C-hour), and the index determined from the latter function is the equivalent age factor (hours).

The use of concrete maturity to predict in-situ strengths requires an initial laboratory testing process to establish a correlation between strength and maturity — often referred to as the strength-maturity relationship — upon which all future field-cured strength predictions are based. Any relationship so developed, however, is specific to the mix design being tested. In lieu of the fact that flexural strength is Caltrans' criterion for opening a newly constructed concrete pavement to traffic, this study set as its primary goal the need to prove that maturity can predict flexural strength of concrete as opposed to the more commonly used compressive strength parameter.

This study encompassed a comprehensive laboratory study to verify the maturity process using two typical Caltrans mix designs with a flyash-portland cement blend. These mix designs contained two different flyash percentages that play a significant role in the strength development trends of the concrete mixtures. Next, each mixture was cured at four different curing regimes, including a standard laboratory limewater bath cure at a nominal (fog room) temperature of 23^{O}C. Maturity relationships were derived for the mixtures cured under this standard laboratory condition, and the derived relationships were used to predict strengths of the concrete mixtures cured at both higher and lower temperature regimes. The actual strength data were compared against the predicted strengths to estimate the magnitude of the errors involved. Data analyses also established the optimum datum temperature and activation energy values to be used in the Nurse-Saul and Arrhenius functions, respectively, for the mix designs tested.

The test results indicate that both the Nurse-Saul and Arrhenius regression equations developed from the standard (room) temperature data where able to predict concrete strengths associated with both cooler (~10^{O}C) and warmer (~37^{O}C) curing temperatures with reasonable accuracy. Further, actual field-derived compressive cylinder and flexural beam strengths from a recent project near Victorville CA, using the same mix design as mix 2 from the present study, yielded similarly accurate in-situ concrete strength predictions (see Appendix E).

5.2 CONCLUSIONS

Based on this analysis, the research team concludes the following:

- Concrete strength gain can be related to the thermal history of the mixture as it hydrates. The two maturity indices calculated using the Nurse-Saul function and the Arrhenius function, the temperature-time factor and the equivalent age respectively, are both equally efficient and accurate in estimating both flexural and compressive strengths.
- Strength-maturity relationships derived for estimating the flexural strength of concrete mixtures can be used to predict the flexural strength of in-situ concrete to a reasonably accurate degree. The errors in prediction are within the tolerance specified by standard strength tests.
- Concrete maturity can be used to predict the compressive strength of a concrete mixture.
- Strength-maturity relationships must be developed for each specific concrete mixture to increase the accuracy and reliability in strength predictions.
- The selection of the right datum temperature in the Nurse-Saul function is crucial to achieving good quality strength predictions. The optimum datum temperature may change with the mix design. For the mix designs used in this study, the optimum datum temperature was determined to be -10^{O}C. The ability to predict both flexural and compressive strength was considered in establishing this value. This datum temperature will be used for all future estimates.
- Likewise, the selection of the appropriate activation energy is important for reliable predictions using the Arrhenius function. For the mix designs used in this study, the optimum activation energy was determined to be 30,000 joules/mole, resulting in minimal overall errors in strength predictions.
- The logarithmic model for strength determination was found to be adequate to define the strength-maturity relationships.
- The effects on strength development of different mix design parameters and curing conditions can be traced through maturity recordings. In this test plan, the strength predictions in mix 1 vs. mix 2 were as expected. The higher percentage of flyash in mix 2 resulted in lower strength gain in the early ages; however, this mix gains higher

long-term strength values relative to mix 1. The strength predictions clearly show these trends. Similarly, mixtures cured at higher temperatures should gain higher early age strengths than mixtures cured at lower temperatures. The predicted strengths clearly show these trends as well.

- Maturity is applicable only for mixtures that have sufficient moisture to hydrate and gain strength during the curing period. An increase in mix temperature without an associated potential for strength gain, i.e. due to the lack of water for proper hydration, is not reflective of a higher maturity of the mixture.
- The curing conditions provided are, in effect, built into the strength-maturity relationships. Therefore, it is imperative to provide optimum curing conditions for strength gain as well as to reflect the actual in-situ curing conditions. Likewise, the maturity relationship developed for a control mixture under laboratory conditions is only applicable for predicting strengths in identical mixtures that are cured under similar conditions. For example, high early age temperatures may tend to distort the strength-maturity relationship because the mixture attains higher early age strengths and lower ultimate strengths. However, based on the findings of this study, this distortion is insignificant, at least for curing temperatures that range between $10^{O}C$ and $38^{O}C$ ($50^{O}F$ and $100^{O}F$). Note that the selection of the datum temperature for the Nurse-Saul maturity function of $-10^{O}C$ and an activation energy of 30,000 Joules/mole for the Arrhenius function also account for any divergence resulting from different initial curing conditions.

In conclusion, this research project suggests that there is an immediate potential for the implementation of concrete maturity technology for Caltrans projects. The study only forms a preliminary verification of this method for predicting in-situ strengths. Adoption of maturity concepts in practice would require a rigorous laboratory testing process through a new California Test Method (CTM) to define the signature strength gain patterns for each individual mix design, for each Caltrans project.

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APPENDICES

Appendix A – Mix Designs

The mix designs used in this study were similar to a concrete mix used for a paving project near Victorville, CA. The mix designs are included in this appendix. The properties of the mix components used in the mixes are as shown in Table A1. The mix design for mixes 1 and 2 are shown in Tables A2 and A3 respectively. Tables A4 and A5 summarize the measured fresh concrete properties—slump, air content and unit weight—during each casting for mixes 1 and 2 respectively.

Table A1. Material properties of mix components

Material	**γ (g/cm3)**	**Water abs (%)**
Cement	3.15	-
Flyash type F	2.14	-
Sand	2.55	0.8%
Coarse 1" (SSD)	2.51	1.0%
Coarse 1½"	Not used	
Water	1.00	-
Pave Air	1.03	-
Masterpave	1.20	-
% Sand of Coarse:	68.7%	-

Table A2. Mix design for mix 1

	Content (lb/yd3)		**Content (lb/ft3)**		**Content (kg/m3)**		Unit proportions	
Cement	482	567	17.85	21.00	285.91	336.33	1.00	0.85
Fly Ash type F	85		3.15		50.42			0.15
Sand	1233	3028	45.66	112.15	731.34	1796.08	5.34	2.17
Coarse 1"	1795		66.48		1064.74			3.17
Coarse 1 1/2"	0		0.00		0.00			0.00
Water	266.78		9.88		158.25		0.47	0.47
Pave Air (oz/yd3) =	8							
Masterpave (oz/yd3) =	22							

Table A3. Mix design for mix 1

	Content (lb/yd3)		**Content (lb/ft3)**		**Content (kg/m3)**		Unit proportions	
Cement	425	567	15.74	21.00	252.10	336.33	1.00	0.75
Fly Ash type F	142		5.26		84.23			0.25
Sand	1224	3006	45.33	111.33	726.04	1783.07	5.30	2.16
Coarse 1"	1782		66.00		1057.03			3.14
Coarse 1 1/2"	0		0.00		0.00			0.00
Water	266.78		9.88		158.25		0.47	0.47
Pave Air (oz/yd3) =	8							
Masterpave (oz/yd3) =	22							

Table A4. Fresh concrete properties for mix 1

Mix, Date of Casting, and age at strength test	Parameter	Mix cast for curing temperature				Average
		38 °C	23 °C	10 °C	AMB	
Mix 1, cast on 11/17/2003, tested at 3 days	Slump, in (ASTM C 143)	1.25	2.00	1.75	2.00	1.75
	Air, % (CTM 504)	3.50	4.00	3.70	4.00	3.80
	Unit Weight, pcf (ASTM C 138)	145	143	144	143	143.7
Mix 1, cast on 11/19/2003, tested at 7 days	Slump, in (ASTM C 143)	1.50	2.25	1.75	2.00	1.88
	Air, % (CTM 504)	4.00	3.70	4.50	3.70	3.98
	Unit Weight, pcf (ASTM C 138)	143	144	143	144	143.2
Mix 1, cast on 11/10/2003, tested at 14 days	Slump, in (ASTM C 143)	1.00	1.75	1.75	2.00	1.63
	Air, % (CTM 504)	3.30	4.00	3.80	4.30	3.85
	Unit Weight, pcf (ASTM C 138)	145	143	143	143	143.5
Mix 1, cast on 11/4/2003, tested at 28 days	Slump, in (ASTM C 143)	1.50	2.25	1.75	2.00	1.88
	Air, % (CTM 504)	3.70	4.00	4.20	3.90	3.95
	Unit Weight, pcf (ASTM C 138)	143	143	143	141	142.4

Table A5. Fresh concrete properties for mix 2

Mix, Date of Casting, and age at strength test	Parameter	Mix cast for curing temperature				Average
		38 °C	23 °C	10 °C	AMB	
Mix 2, cast on 11/21/2003, tested at 3 days	Slump, in (ASTM C 143)	1.75	2.25	1.75	2.25	2.00
	Air, % (CTM 504)	2.40	3.00	2.40	3.00	2.70
	Unit Weight, pcf (ASTM C 138)	142.9	144.1	144.9	143.7	143.9
Mix 2, cast on 11/25/2003, tested at 7 days	Slump, in (ASTM C 143)	1.25	1.50	1.50	1.50	1.44
	Air, % (CTM 504)	3.20	2.40	2.40	2.60	2.65
	Unit Weight, pcf (ASTM C 138)	143	146	146	145	145.0
Mix 2, cast on 11/12/2003, tested at 14 days	Slump, in (ASTM C 143)	1.25	2.00	2.00	2.00	1.81
	Air, % (CTM 504)	3.40	2.60	2.60	2.60	2.80
	Unit Weight, pcf (ASTM C 138)	146	145	145	145	145.2
Mix 2, cast on 11/6/2003, tested at 28 days	Slump, in (ASTM C 143)	1.50	1.50	1.75	1.75	1.63
	Air, % (CTM 504)	2.20	2.40	2.30	2.40	2.33
	Unit Weight, pcf (ASTM C 138)	145	145	146	145	145.2

Appendix B – Summary of Strength and Curing Temperature Data

This appendix summarizes the strength data measured in the lab for all specimens at various curing temperatures. The strength data includes both flexural strength and compressive strength. For each temperature and age, four beams were tested for flexural strength and three cylinders were tested for compressive strength. Of these, one beam and one cylinder contained an embedded maturity gage. The temperature data presented refer to the temperatures measured in this specimen at the end of the curing period, as described below.

Note that the average strength values were used as a representative strength value for each test age. It was ensured that the average strength was within 10 percent of each individual strength value. In computing the average strength values, the strength values from the specimens with an embedded gage were disregarded. However, in cases where the average strength varied exceedingly from an individual strength value, the strength determined from the specimens with embedded gages were used in computing the average. Tables B1 through B16 summarize the strength data of all samples.

The curing rooms were kept under controlled conditions of $23^{O}C$, $10^{O}C$, and $38^{O}C$ curing regimes, while the ambient curing conditions had temperature variations depending on the weather conditions in Sacramento, CA during that period. Temperature readings were monitored for all the samples through out the curing phase.

Typically, during the initial curing in the first 24 hours, the sample is at higher temperatures due to heat of hydration. After the initial heat of hydration is liberated, the mix attains the temperature levels characteristic of the curing condition. The temperature measured at the end of the curing period, which is well past the initial hydration process, could also serve as a good indication of the temperature level maintained in that particular curing regime. Note that this is not applicable to the specimens cured in ambient conditions. Table B17 shows a summary of the temperature data recorded in the three controlled curing regimes.

Table B1. Compressive strength data at 3 days for mix 1 (15% Flyash).

Test Date	Sample Number - Curing Temperature	Age, days	Cyl. Area, in^2	Total Load, lb	Comp. Strength, lb/in^2	Average Comp. Str., lb/in^2	Percent Variation
11/20/2003	1-38 C	3	28.27	97,960	3,465	3,500	1.00
	2-38 C	3	28.27	99,960	3,535		1.00
	3*-38 C	3	28.27	101,700	3,597		2.77
11/20/2003	1-23 C	3	28.27	96,030	3,396	3,401	0.15
	2- 23 C	3	28.27	96,310	3,406		0.15
	3*- 23 C	3	28.27	91,690	3,243		4.65
11/20/2003	1-10C	3	28.27	83,240	2,944	2,928	0.56
	2-10C	3	28.27	82,300	2,911		0.56
	3*-10C	3	28.27	74,100	2,621		10.47
11/20/2003	1-AMB	3	28.27	91,200	3,226	3,234	0.23
	2-AMB	3	28.27	9,165	3,241		0.23
	3*-AMB	3	28.27	83,030	2,937		9.17

* Specimen with maturity sensor

Table B2. Flexural strength data at 3 days for mix 1 (15% Flyash).

Date	Sample Number - Curing Temperature	Age, days	Span, inch	Width, inch		Mod. Of Rup.		Avg flx. Str., lb/in^2	Percent Variation
				B	D	Load, lb	lb/in^2		
11/20/2003	1-38C	3	18	6.0050	6.0000	5590	470	467	0.71
	2-38C	3	18	6.0620	5.9970	5800	480		2.86
	3-38C	3	18	5.9930	6.0450	5420	450		3.57
	4*-38C	3	18	6.0030	6.0730	5560	450		3.57
11/20/2003	1-23 C	3	18	6.0500	5.9950	6130	510	520	1.92
	2- 23 C	3	18	6.0190	6.0350	6290	520		0.00
	3- 23 C	3	18	6.0460	6.0440	6450	530		1.92
	4*- 23 C	3	18	5.9670	6.0530	5890	490		5.77
11/20/2003	1-10C	3	18	6.0480	6.0700	5820	470	470	0.00
	2-10C	3	18	6.0200	6.0170	5320	440		6.38
	3-10C	3	18	6.0790	6.0360	6120	500		6.38
	4*-10C	3	18	6.0800	6.0360	5370	440		6.38
11/20/2003	1-AMB	3	18	5.9840	6.0570	5320	440	295	49.15
	2-AMB	3	18	6.0090	6.0500	2990	250		15.25
	3-AMB	3	18	5.9970	6.0420	4160	340		15.25
	4*-AMB	3	18	6.0430	6.1100	3690	290		1.69

* Specimen with maturity sensor

Table B3. Compressive strength data at 3 days for mix 2 (25% Flyash).

Test Date	Sample Number - Curing Temperature	Age, days	Cyl. Area, in^2	Total Load, lb	Comp. Strength, lb/in^2	Average Comp. Str., lb/in^2	Percent Variation
11/24/2003	1-38 C	3	28.27	85,810	3,035	3,051	0.52
	2-38 C	3	28.27	86,830	3,067		0.52
	3*-38 C	3	28.27	93,620	3,311		8.52
11/24/2003	1-23 C	3	28.27	91,200	3,226	3,258	0.98
	2- 23 C	3	28.27	93,020	3,290		0.98
	3*- 23 C	3	28.27	81,230	2,873		11.82
11/24/2003	1-10C	3	28.27	69,920	2,473	2,566	3.62
	2-10C	3	28.27	75,190	2,659		3.62
	3*-10C	3	28.27	70,900	2,508		2.26
11/24/2003	1-AMB	3	28.27	55,290	1,955	2,014	2.93
	2-AMB	3	28.27	58,600	2,073		2.93
	3*-AMB	3	28.27	51,330	1,815		9.88

* Specimen with maturity sensor

Table B4. Flexural strength data at 3 days for mix 2 (25% Flyash).

Date	Sample Number - Curing Temperature	Age, days	Span, inch	Width, inch		Mod. Of Rup.		Avg flx. Str., lb/in^2	Percent Variation
				B	D	Load, lb	lb/in^2		
11/24/2003	1-38C	3	18	5.9900	6.0800	4930	400	403	0.83
	2-38C	3	18	5.9900	6.0800	4960	400		0.83
	3-38C	3	18	5.9900	6.0900	5100	410		1.65
	4*-38C	3	18	6.0400	6.0600	5580	450		11.57
11/24/2003	1-23 C	3	18	6.0400	6.0700	6200	500	487	2.74
	2- 23 C	3	18	6.0500	6.0600	5790	470		3.42
	3- 23 C	3	18	6.0400	6.0500	5960	490		0.68
	4*- 23 C	3	18	6.0600	6.0600	5680	460		5.48
11/24/2003	1-10C	3	18	6.0000	6.0500	4710	390	397	1.68
	2-10C	3	18	6.0000	6.0700	4800	390		1.68
	3-10C	3	18	6.0200	6.0700	5070	410		3.36
	4*-10C	3	18	6.0300	6.0300	5290	430		8.40
11/24/2003	1-AMB	3	18	6.0300	6.0400	5680	460	433	6.15
	2-AMB	3	18	6.0400	6.0400	4960	410		5.38
	3-AMB	3	18	6.0500	6.0500	5220	430		0.77
	4*-AMB	3	18	6.0800	6.0800	4800	390		10.00

* Specimen with maturity sensor

Table B5. Compressive strength data at 7 days for mix 1 (15% Flyash).

Test Date	Sample Number - Curing Temperature	Age, days	Cyl. Area, in^2	Total Load, lb	Comp. Strength, lb/in^2	Average Comp. Str., lb/in^2	Percent Variation
11/26/2003	1-38 C	7	28.27	117,300	4,149	4,209	1.43
	2-38 C	7	28.27	120,700	4,269		1.43
	3*-38 C	7	28.27	115,400	4,081		3.04
11/26/2003	1-23 C	7	28.27	113,100	4,000	4,075	1.83
	2- 23 C	7	28.27	117,300	4,149		1.83
	3*- 23 C	7	28.27	116,400	4,117		1.04
11/26/2003	1-10C	7	28.27	110,600	3,912	3,847	1.70
	2-10C	7	28.27	106,900	3,781		1.70
	3*-10C	7	28.27	102,800	3,636		5.47
11/26/2003	1-AMB	7	28.27	118,800	4,202	4,027	4.35
	2-AMB	7	28.27	108,900	3,852		4.35
	3*-AMB	7	28.27	104,200	3,685		8.49

* Specimen with maturity sensor

Table B6. Flexural strength data at 7 days for mix 1 (15% Flyash).

Date	Sample Number - Curing Temperature	Age, days	Span, inch	Width, inch		Mod. Of Rup.		Avg flx. Str., lb/in^2	Percent Variation
				B	D	Load, lb	lb/in^2		
11/26/2003	1-38C	7	18	6.0000	6.0700	7090	580	577	0.58
	2-38C	7	18	6.0000	6.0400	7130	590		2.31
	3-38C	7	18	6.0200	6.0800	6980	560		2.89
	4*-38C	7	18	6.0200	6.0700	7080	570		1.16
11/26/2003	1-23 C	7	18	6.0400	6.0600	7480	610	583	4.57
	2- 23 C	7	18	6.0000	6.0500	6940	570		2.29
	3- 23 C	7	18	5.9900	6.0500	6990	570		2.29
	4*- 23 C	7	18	6.0400	6.0300	7200	590		1.14
11/26/2003	1-10C	7	18	6.0600	6.0400	6860	560	540	3.70
	2-10C	7	18	6.0200	6.0200	6420	530		1.85
	3-10C	7	18	5.9900	6.0300	6460	530		1.85
	4*-10C	7	18	6.0900	6.0600	6540	530		1.85
11/26/2003	1-AMB	7	18	6.0000	6.0500	5700	470	450	4.44
	2-AMB	7	18	5.9900	6.0400	5130	420		6.67
	3-AMB	7	18	6.0600	6.0400	5620	460		2.22
	4*-AMB	7	18	6.1000	6.0400	5970	480		6.67

* Specimen with maturity sensor

Table B7. Compressive strength data at 8 days for mix 2 (25% Flyash).

Test Date	Sample Number - Curing Temperature	Age, days	Cyl. Area, in^2	Total Load, lb	Comp. Strength, lb/in^2	Average Comp. Str., lb/in^2	Percent Variation
12/3/2003	1-38 C	8	28.27	105,200	3,721	3,693	0.77
	2-38 C	8	28.27	103,600	3,664		0.77
	3*-38 C	8	28.27	102,100	3,611		2.21
12/3/2003	1-23 C	8	28.27	118,900	4,205	4,296	2.11
	2- 23 C	8	28.27	124,000	4,386		2.11
	3*- 23 C	8	28.27	114,600	4,053		5.65
12/3/2003	1-10C	8	28.27	121,400	4,294	4,154	3.37
	2-10C	8	28.27	113,500	4,014		3.37
	3*-10C	8	28.27	114,300	4,043		2.67
12/3/2003	1-AMB	8	28.27	103,000	3,643	3,631	0.34
	2-AMB	8	28.27	99,340	6,513		79.40
	3*-AMB	8	28.27	102,300	3,618		0.34

* Specimen with maturity sensor

Table B8. Flexural strength data at 8 days for mix 2 (25% Flyash).

Date	Sample Number - Curing Temperature	Age, days	Span, inch	Width, inch		Mod. Of Rup.		Avg flx. Str., lb/in^2	Percent Variation
				B	D	Load, lb	lb/in^2		
12/3/2003	1-38C	8	18	5.9900	6.0700	6910	560	567	1.18
	2-38C	8	18	5.9700	6.0700	6620	540		4.71
	3-38C	8	18	6.0400	6.0900	7470	600		5.88
	4*-38C	8	18	5.9600	6.0600	7430	610		7.65
12/3/2003	1-23 C	8	18	6.0000	6.0600	6660	540	567	4.71
	2- 23 C	8	18	6.0000	6.0600	7120	580		2.35
	3- 23 C	8	18	6.0200	6.0500	7100	580		2.35
	4*- 23 C	8	18	5.9900	6.0700	6880	560		1.18
12/3/2003	1-10C	8	18	6.0000	6.0600	6460	530	520	1.92
	2-10C	8	18	6.0300	6.0500	5990	490		5.77
	3-10C	8	18	6.0500	6.0600	6610	540		3.85
	4*-10C	8	18	6.0400	6.0500	6850	560		7.69
12/3/2003	1-AMB	8	18	5.9800	6.0400	6520	540	527	2.53
	2-AMB	8	18	6.0300	6.0400	6540	530		0.63
	3-AMB	8	18	5.9600	6.0600	6250	510		3.16
	4*-AMB	8	18	5.9800	6.0600	6390	520		1.27

* Specimen with maturity sensor

Table B9. Compressive strength data at 14 days for mix 1 (15% Flyash).

Test Date	Sample Number - Curing Temperature	Age, days	Cyl. Area, in^2	Total Load, lb	Comp. Strength, lb/in^2	Average Comp. Str., lb/in^2	Percent Variation
11/24/2003	1-38 C	14	28.27	127,700	4,516	4,564	1.05
	2-38 C	14	28.27	130,400	4,612		1.05
	3*-38 C	14	28.27	119,200	4,216		7.62
11/24/2003	1-23 C	14	28.27	131,900	4,665	4,538	2.81
	2- 23 C	14	28.27	124,700	4,410		2.81
	3*- 23 C	14	28.27	129,600	4,584		1.02
11/24/2003	1-10C	14	28.27	138,300	4,891	4,883	0.17
	2-10C	14	28.27	137,800	4,874		0.17
	3*-10C	14	28.27	131,500	4,651		4.74
11/24/2003	1-AMB	14	28.27	81,020	2,865	4,015	28.63
	2-AMB	14	28.27	113,200	4,004		0.26
	3*-AMB	14	28.27	113,800	4,025		0.26

* Specimen with maturity sensor

Table B10. Flexural strength data at 14 days for mix 1 (15% Flyash).

Date	Sample Number - Curing Temperature	Age, days	Span, inch	Width, inch		Mod. Of Rup.		Avg flx. Str., lb/in^2	Percent Variation
				B	D	Load, lb	lb/in^2		
11/24/2003	1-38C	14	18	5.9900	6.0600	7320	600	587	2.27
	2-38C	14	18	6.0000	6.0700	7200	590		0.57
	3-38C	14	18	6.0000	6.0500	6980	570		2.84
	4*-38C	14	18	6.0200	6.0700	7220	590		0.57
11/24/2003	1-23 C	14	18	6.0100	6.0300	7310	600	603	0.55
	2- 23 C	14	18	6.0200	6.0300	7450	610		1.10
	3- 23 C	14	18	5.9800	6.0700	7370	600		0.55
	4*- 23 C	14	18	6.0800	6.0600	7660	620		2.76
11/24/2003	1-10C	14	18	6.0000	6.0300	7670	630	613	2.72
	2-10C	14	18	5.9500	6.0400	7660	640		4.35
	3-10C	14	18	6.0000	6.0700	6950	570		7.07
	4*-10C	14	18	6.0600	6.0100	7220	590		3.80
11/24/2003	1-AMB	14	18	6.0500	5.9700	5730	480	500	4.00
	2-AMB	14	18	5.9900	6.0300	6590	540		8.00
	3-AMB	14	18	5.9600	6.0500	5790	480		4.00
	4*-AMB	14	18	6.0400	6.0300	4470	370		26.00

* Specimen with maturity sensor

Table B11. Compressive strength data at 14 days for mix 2 (25% Flyash).

Test Date	Sample Number - Curing Temperature	Age, days	Cyl. Area, in^2	Total Load, lb	Comp. Strength, lb/in^2	Average Comp. Str., lb/in^2	Percent Variation
11/26/2003	1-38 C	14	28.27	147,900	5,231	5,291	1.13
	2-38 C	14	28.27	151,300	5,351		1.13
	3*-38 C	14	28.27	12,900	4,562		13.78
11/26/2003	1-23 C	14	28.27	132,970	4,703	4,670	0.71
	2- 23 C	14	28.27	131,100	4,637		0.71
	3*- 23 C	14	28.27	123,500	4,368		6.47
11/26/2003	1-10C	14	28.27	132,400	4,683	4,706	0.49
	2-10C	14	28.27	133,700	4,729		0.49
	3*-10C	14	28.27	132,900	4,700		0.13
11/26/2003	1-AMB	14	28.27	100,500	3,554	3,758	5.42
	2-AMB	14	28.27	112,000	3,961		5.42
	3*-AMB	14	28.27	110,500	3,908		4.01

* Specimen with maturity sensor

Table B12. Flexural strength data at 14 days for mix 2 (25% Flyash).

Date	Sample Number - Curing Temperature	Age, days	Span, inch	Width, inch		Mod. Of Rup.		Avg flx. Str., lb/in^2	Percent Variation
				B	D	Load, lb	lb/in^2		
11/26/2003	1-38C	14	18	5.9400	6.0600	8910	740	733	0.91
	2-38C	14	18	5.9900	6.0400	8070	660		10.00
	3-38C	14	18	6.0400	6.0500	9840	800		9.09
	4*-38C	14	18	6.0300	6.0600	8520	690		5.91
11/26/2003	1-23 C	14	18	5.9800	6.0700	7500	610	623	2.14
	2- 23 C	14	18	5.9900	6.0300	7570	630		1.07
	3- 23 C	14	18	6.0000	6.0200	7650	630		1.07
	4*- 23 C	14	18	6.0000	6.0600	7380	600		3.74
11/26/2003	1-10C	14	18	5.9800	6.0400	7020	580	580	0.00
	2-10C	14	18	6.0100	6.0200	7300	600		3.45
	3-10C	14	18	6.0500	6.0200	6780	560		3.45
	4*-10C	14	18	6.0600	6.0400	7610	620		6.90
11/26/2003	1-AMB	14	18	5.9500	6.0600	6500	540	477	13.29
	2-AMB	14	18	6.0100	6.0700	5700	460		3.50
	3-AMB	14	18	5.9700	6.0200	5170	430		9.79
	4*-AMB	14	18	6.0200	6.0500	6360	520		9.09

* Specimen with maturity sensor

Table B13. Compressive strength data at 29 days for mix 1 (15% Flyash).

Test Date	Sample Number - Curing Temperature	Age, days	Cyl. Area, in^2	Total Load, lb	Comp. Strength, lb/in^2	Average Comp. Str., lb/in^2	Percent Variation
12/3/2003	1-38 C	29	28.27	124,700	5,489	5,277	4.02
	2-38 C	29	28.27	130,300	5,065		4.02
	3*-38 C	29	28.27	143,500	5,401		2.35
12/3/2003	1-23 C	29	28.27	134,900	4,771	5,008	4.73
	2- 23 C	29	28.27	148,300	5,245		4.73
	3*- 23 C	29	28.27	130,600	4,619		7.77
12/3/2003	1-10C	29	28.27	155,200	4,410	4,509	2.20
	2-10C	29	28.27	143,200	4,608		2.20
	3*-10C	29	28.27	152,700	5,075		12.55
12/3/2003	1-AMB	29	28.27	138,700	4,906	4,892	0.30
	2-AMB	29	28.27	137,900	4,877		0.30
	3*-AMB	29	28.27	97,940	3,464		29.18

* Specimen with maturity sensor

Table B14. Flexural strength data at 29 days for mix 1 (15% Flyash).

Date	Sample Number - Curing Temperature	Age, days	Span, inch	Width, inch		Mod. Of Rup.		Avg flx. Str., lb/in^2	Percent Variation
				B	D	Load, lb	lb/in^2		
12/3/2003	1-38C	29	18	5.9900	6.0300	7490	620	660	6.06
	2-38C	29	18	6.0300	6.0300	8350	690		4.55
	3-38C	29	18	6.0000	6.0200	8050	670		1.52
	4*-38C	29	18	5.9700	6.0200	7490	620		6.06
12/3/2003	1-23 C	29	18	6.0200	6.0400	8530	700	687	1.94
	2- 23 C	29	18	5.9800	6.0600	8390	690		0.49
	3- 23 C	29	18	5.9900	6.0300	8110	670		2.43
	4*- 23 C	29	18	6.1000	6.0200	7920	640		6.80
12/3/2003	1-10C	29	18	6.0100	5.9900	7490	630	623	1.07
	2-10C	29	18	5.9000	5.9500	7120	610		2.14
	3-10C	29	18	6.0000	5.9600	7470	630		1.07
	4*-10C	29	18	6.0200	6.0000	7200	600		3.74
12/3/2003	1-AMB	29	18	6.0000	6.0200	7310	600	460	30.43
	2-AMB	29	18	6.0300	6.0400	5680	460		0.00
	3-AMB	29	18	6.0000	6.0300	5610	460		0.00
	4*-AMB	29	18	6.0700	6.0400	5800	470		2.17

* Specimen with maturity sensor

Table B15. Compressive strength data at 28 days for mix 2 (25% Flyash).

Test Date	Sample Number - Curing Temperature	Age, days	Cyl. Area, in^2	Total Load, lb	Comp. Strength, lb/in^2	Average Comp. Str., lb/in^2	Percent Variation
12/4/2003	1-38 C	28	28.27	144,900	5,125	5,056	1.36
	2-38 C	28	28.27	141,000	4,987		1.36
	3*-38 C	28	28.27	150,900	5,337		5.56
12/4/2003	1-23 C	28	28.27	157,500	5,570	5,540	0.54
	2- 23 C	28	28.27	155,800	5,510		0.54
	3*- 23 C	28	28.27	145,700	5,153		6.99
12/4/2003	1-10C	28	28.27	156,600	5,539	5,511	0.52
	2-10C	28	28.27	155,000	5,482		0.52
	3*-10C	28	28.27	150,300	5,316		3.53
12/4/2003	1-AMB	28	28.27	140,500	4,969	4,976	0.14
	2-AMB	28	28.27	140,900	4,983		0.14
	3*-AMB	28	28.27	134,700	4,764		4.26

* Specimen with maturity sensor

Table B16. Flexural strength data at 28 days for mix 2 (25% Flyash).

Date	Sample Number - Curing Temperature	Age, days	Span, inch	Width, inch		Mod. Of Rup.		Avg flx. Str., lb/in^2	Percent Variation
				B	D	Load, lb	lb/in^2		
12/4/2003	1-38C	28	18	5.9500	6.0300	9530	790	760	3.95
	2-38C	28	18	5.9500	6.0500	8640	710		6.58
	3-38C	28	18	5.9600	6.0500	9450	780		2.63
	4*-38C	28	18	6.0100	6.0700	10210	830		9.21
12/4/2003	1-23 C	28	18	6.0100	6.0300	8460	700	703	0.47
	2- 23 C	28	18	5.9800	6.0500	8510	700		0.47
	3- 23 C	28	18	5.9600	6.0300	8600	710		0.95
	4*- 23 C	28	18	6.0300	6.0400	7420	610		13.27
12/4/2003	1-10C	28	18	5.9900	6.0200	7400	620	657	5.58
	2-10C	28	18	6.0000	6.0400	7950	650		1.02
	3-10C	28	18	5.9900	6.0500	8510	700		6.60
	4*-10C	28	18	6.0200	6.0200	7640	630		4.06
12/4/2003	1-AMB	28	18	6.0200	6.0100	7970	660	627	5.32
	2-AMB	28	18	6.0000	6.0400	7210	590		5.85
	3-AMB	28	18	5.9500	6.0000	7530	630		0.53
	4*-AMB	28	18	6.0700	6.0400	7540	610		2.66

* Specimen with maturity sensor

Table B.17. Temperature data recorded during the curing regime for the controlled curing conditions

Curing temp	Time Data recorded for, hour	Temp at last record, degC	Max recorded, degC	Time at Max temp, hours	Min recorded, degC	Time at Min temp, hours	Max temp after 24 hrs, degC	Min temp after 24 hrs, degC	Avg temp after 24 hrs, degC
10C	698.0	10	24	0.00	9	73.50	12	9	10.1
10C	191.0	10	23	0.25	10	76.75	11	10	10.5
23C	189.6	25	30	12.50	20	0.00	26	25	25.0
23C	695.5	25	33	11.50	22	0.00	26	24	25.0
38C	192.0	37	41	30.50	23	0.00	41	37	39.6
38C	697.9	33	41	7.50	24	0.00	38	33	35.7

Appendix C – Temperature-Time Factor Correlations to Strength Using the Nurse-Saul Equation

This appendix contains the analysis performed to establish the optimum datum temperature for the mixes used in the study. For each strength category (mix 1 flexural, mix 2 flexural, mix 1 compressive, and mix 2 compressive), the strength maturity relationship was established using the sample cured in a limewater bath in the fog room at 23^{O}C. The maturity index used in the analysis was the temperature-time factor determined using the Nurse-Saul function. The relationship developed is a logarithmic function of the form:

Strength = A*log (maturity) + B.

This strength-maturity relationship was used to predict the strength of the samples cured at 10^{O}C, and 38^{O}C. The predicted strength was compared against the measured strength for the two mixes and the prediction errors were estimated. The above exercise was repeated for datum temperature values of 0^{O}C, -5^{O}C, and -10^{O}C.

This appendix presents the results in a tabulated format. The term referred to as the coefficient is the coefficient "A" in the above equation while the term "constant" refers to the regression constant "B" is the equation.

As noted earlier, the data for the samples cured at ambient conditions were very erratic and therefore not used in the analyses. However, the data is reported in this appendix.

Table C1. Flexural strength predictions using the Nurse-Saul Method for mixes 1 and 2 for curing temperatures of $10^{O}C$ and $38^{O}C$ using $23^{O}C$ as reference.

FLEXURAL STRENGTH FOR MIXES 1 AND 2													
23 vs. 10C	14F (-10C)							14F (-10C)					
	Mix 1 Flexural strength							Mix 2 flexural strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	70.986	-40.053	483	470	2.7%		3 day	98.404	-291.96	431	397	8.0%
	7 day	70.986	-40.053	542	540	0.3%		7 day	98.404	-291.96	523	520	0.6%
	14 day	70.986	-40.053	587	613	-4.6%		14 day	98.404	-291.96	579	580	-0.1%
	28 day	70.986	-40.053	637	623	2.2%		28 day	98.404	-291.96	643	657	-2.1%
	23F (-5C)							23F (-5C)					
	Mix 1 Flexural strength							Mix 2 flexural strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	71.26	-31.525	475	470	1.1%		3 day	98.725	-279.52	420	397	5.5%
	7 day	71.26	-31.525	534	540	-1.2%		7 day	98.725	-279.52	511	520	-1.8%
	14 day	71.26	-31.525	577	613	-6.2%		14 day	98.725	-279.52	568	580	-2.2%
	28 day	71.26	-31.525	628	623	0.7%		28 day	98.725	-279.52	630	657	-4.2%
	Datum Temperature of 32F (0C)							Datum Temperature of 32F (0C)					
	Mix 1 flexural strength							Mix 2 flexural strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	71.655	-21.865	463	470	-1.6%		3 day	99.176	-265.26	402	397	1.3%
	7 day	71.655	-21.865	521	540	-3.7%		7 day	99.176	-265.26	490	520	-6.1%
	14 day	71.655	-21.865	562	613	-9.1%		14 day	99.176	-265.26	548	580	-5.8%
	28 day	71.655	-21.865	612	623	-1.8%		28 day	99.176	-265.26	608	657	-8.0%
23 vs. 38C	Datum Temperature of 14F (-10C)							Datum Temperature of 14F (-10C)					
	Mix 1 Flexural strength							Mix 2 flexural strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	70.986	-40.053	541	467	13.7%		3 day	98.404	-291.96	520	403	22.4%
	7 day	70.986	-40.053	606	577	4.9%		7 day	98.404	-291.96	605	567	6.4%
	14 day	70.986	-40.053	645	587	9.0%		14 day	98.404	-291.96	669	733	-9.7%
	28 day	70.986	-40.053	695	660	5.1%		28 day	98.404	-291.96	724	760	-5.0%
	Datum Temperature of 23F (-5C)							Datum Temperature of 23F (-5C)					
	Mix 1 Flexural strength							Mix 2 flexural strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	71.26	-31.525	544	467	14.2%		3 day	98.725	-279.52	525	403	23.2%
	7 day	71.26	-31.525	610	577	5.5%		7 day	98.725	-279.52	610	567	7.1%
	14 day	71.26	-31.525	647	587	9.4%		14 day	98.725	-279.52	674	733	-8.8%
	28 day	71.26	-31.525	698	660	5.5%		28 day	98.725	-279.52	728	760	-4.4%
	Datum Temperature of 32F (0C)							Datum Temperature of 32F (0C)					
	Mix 1 flexural strength							Mix 2 flexural strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	71.655	-21.865	548	467	14.9%		3 day	99.176	-265.26	532	403	24.2%
	7 day	71.655	-21.865	616	577	6.3%		7 day	99.176	-265.26	616	567	8.0%
	14 day	71.655	-21.865	652	587	10.0%		14 day	99.176	-265.26	682	733	-7.6%
	28 day	71.655	-21.865	703	660	6.1%		28 day	99.176	-265.26	734	760	-3.5%

Table C2. Compressive strength predictions using the Nurse-Saul Method for mixes 1 and 2 for curing temperatures of 10^{O}C and 38^{O}C using 23^{O}C as reference.

COMPRESSIVE STRENGTH FOR MIXES 1 AND 2													
23 vs. 10C	14F (-10C)							14F (-10C)					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	718.66	-2207.3	3,077	2,928	4.9%		3 day	1011.9	-4677.8	2,749	2,566	6.7%
	7 day	718.66	-2207.3	3,661	3,847	-5.1%		7 day	1011.9	-4677.8	3,686	4,154	-12.7%
	14 day	718.66	-2207.3	4,156	-	-		14 day	1011.9	-4677.8	4,282	4,706	-9.9%
	28 day	718.66	-2207.3	4,648	-	-		28 day	1011.9	-4677.8	4,950	5,511	-11.3%
	23F (-5C)							23F (-5C)					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	720.79	-2114.8	2,996	2,928	2.3%		3 day	1014.3	-4541.5	2,633	2,566	2.5%
	7 day	720.79	-2114.8	3,575	3,847	-7.6%		7 day	1014.3	-4541.5	3,555	4,154	-16.9%
	14 day	720.79	-2114.8	4,069	0	-		14 day	1014.3	-4541.5	4,161	4,706	-13.1%
	28 day	720.79	-2114.8	4,553	0	-		28 day	1014.3	-4541.5	4,820	5,511	-14.3%
	Datum Temperature of 32F (0C)							Datum Temperature of 32F (0C)					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	723.78	-2008.7	2,866	2,928	-2.2%		3 day	1017.7	-4383.6	2445	2,566	-5.0%
	7 day	723.78	-2008.7	3,432	3,847	-12.1%		7 day	1017.7	-4383.6	3336	4,154	-24.5%
	14 day	723.78	-2008.7	3,926	-	-		14 day	1017.7	-4383.6	3962	4,706	-18.8%
	28 day	723.78	-2008.7	4,392	-	-		28 day	1017.7	-4383.6	4602	5,511	-19.7%
23 vs. 38C	Datum Temperature of 14F (-10C)							Datum Temperature of 14F (-10C)					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	718.66	-2207.3	3,675	3,500	4.8%		3 day	1011.9	-4677.8	3,683	3,051	17.2%
	7 day	718.66	-2207.3	4,340	4,209	3.0%		7 day	1011.9	-4677.8	4,572	3,693	19.2%
	14 day	718.66	-2207.3	4,725	4,564	3.4%		14 day	1011.9	-4677.8	5,205	-	-
	28 day	718.66	-2207.3	5,238	5,277	-0.7%		28 day	1011.9	-4677.8	5,773	5,056	12.4%
	Datum Temperature of 23F (-5C)							Datum Temperature of 23F (-5C)					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	720.79	-2114.8	3,708	3,500	5.6%		3 day	1014.3	-4541.5	3,740	3,051	18.4%
	7 day	720.79	-2114.8	4,382	4,209	3.9%		7 day	1014.3	-4541.5	4,620	3,693	20.1%
	14 day	720.79	-2114.8	4,755	4,564	4.0%		14 day	1014.3	-4541.5	5,262	-	-
	28 day	720.79	-2114.8	5,269	5,277	-0.2%		28 day	1014.3	-4541.5	5,816	5,056	13.1%
	Datum Temperature of 32F (0C)							Datum Temperature of 32F (0C)					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	723.78	-2008.7	3753	3,500	6.7%		3 day	1017.7	-4383.6	3816	3,051	20.0%
	7 day	723.78	-2008.7	4437	4,209	5.1%		7 day	1017.7	-4383.6	4684	3,693	21.2%
	14 day	723.78	-2008.7	4796	4,564	4.8%		14 day	1017.7	-4383.6	5338	-	-
	28 day	723.78	-2008.7	5310	5,277	0.6%		28 day	1017.7	-4383.6	5875	5,056	13.9%

Table C3. Flexural strength predictions using the Nurse-Saul Method for mixes 1 and 2 for the “ambient” curing condition, using 23^{O}C as reference.

23 vs. Ambient	Datum Temperature of 14F (-10C)							Datum Temperature of 14F (-10C)					
	Mix 1 Flexural strength							Mix 2 flexural strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	70.986	-40.053	504	295	41.4%		3 day	98.404	-291.96	461	433	6.0%
	7 day	70.986	-40.053	559	450	19.5%		7 day	98.404	-291.96	551	527	4.4%
	14 day	70.986	-40.053	611	500	18.2%		14 day	98.404	-291.96	610	-	-
	28 day	70.986	-40.053	662	-	-		28 day	98.404	-291.96	677	627	7.4%
	Datum Temperature of 23F (-5C)							Datum Temperature of 23F (-5C)					
	Mix 1 Flexural strength							Mix 2 flexural strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	71.26	-31.525	501	295	41.1%		3 day	98.725	-279.52	457	433	5.3%
	7 day	71.26	-31.525	556	450	19.0%		7 day	98.725	-279.52	546	527	3.6%
	14 day	71.26	-31.525	608	500	17.8%		14 day	98.725	-279.52	606	-	-
	28 day	71.26	-31.525	659	-	-		28 day	98.725	-279.52	673	627	6.9%
	Datum Temperature of 32F (0C)							Datum Temperature of 32F (0C)					
	Mix 1 flexural strength							Mix 2 flexural strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	71.655	-21.865	497	295	40.6%		3 day	99.176	-265.26	452	433	4.2%
	7 day	71.655	-21.865	551	450	18.3%		7 day	99.176	-265.26	539	527	2.3%
	14 day	71.655	-21.865	605	500	17.3%		14 day	99.176	-265.26	601	-	-
	28 day	71.655	-21.865	656	-	-		28 day	99.176	-265.26	667	627	6.1%

Table C4. Compressive strength predictions using Nurse-Saul Method for mixes 1 and 2 for the “ambient” curing condition, using 23^{O}C as reference.

23 vs. Ambient	Datum Temperature of 14F (-10C)							Datum Temperature of 14F (-10C)					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	718.66	-2207.3	3307	3,234	2.2%		3 day	1011.9	-4677.8	3014	2,014	33.2%
	7 day	718.66	-2207.3	3818	4,027	-5.5%		7 day	1011.9	-4677.8	3881	3,631	6.5%
	14 day	718.66	-2207.3	4394	4,015	8.6%		14 day	1011.9	-4677.8	4596	3,758	18.2%
	28 day	718.66	-2207.3	4907	4,892	0.3%		28 day	1011.9	-4677.8	5300	4,976	6.1%
	Datum Temperature of 23F (-5C)							Datum Temperature of 23F (-5C)					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	720.79	-2114.8	3284	3,234	1.5%		3 day	1014.3	-4541.5	2967	2,014	32.1%
	7 day	720.79	-2114.8	3775	4,027	-6.7%		7 day	1014.3	-4541.5	3807	3,631	4.6%
	14 day	720.79	-2114.8	4370	4,015	8.1%		14 day	1014.3	-4541.5	4560	3,758	17.6%
	28 day	720.79	-2114.8	4882	4,892	-0.2%		28 day	1014.3	-4541.5	5264	4,976	5.5%
	Datum Temperature of 32F (0C)							Datum Temperature of 32F (0C)					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	723.78	-2008.7	3250	3,234	0.5%		3 day	1017.7	-4383.6	2898	2,014	30.5%
	7 day	723.78	-2008.7	3710	4,027	-8.6%		7 day	1017.7	-4383.6	3692	3,631	1.7%
	14 day	723.78	-2008.7	4334	4,015	7.4%		14 day	1017.7	-4383.6	4508	3,758	16.7%
	28 day	723.78	-2008.7	4845	4,892	-1.0%		28 day	1017.7	-4383.6	5211	4,976	4.5%

Appendix D – Equivalent Age Factor Correlations to Strength Using the Arrhenius Equation

This appendix contains the analysis performed to establish the optimum activation energy for the mixes used in the study. For each strength category (mix 1 flexural, mix 2 flexural, mix 1 compressive, and mix 2 compressive), the strength maturity relationship was established using the sample cured in a limewater bath in the fog room at $23^{O}C$. The maturity index used in the analysis was the equivalent age factor determined using the Arrhenius function. The relationship developed was a logarithmic function of the form:

Strength = A*log (maturity) + B.

This strength-maturity relationship was used to predict the strength of the samples cured at $10^{O}C$ and $38^{O}C$. The predicted strength was compared against the measured strength for the two mixes and the prediction errors were estimated. The above exercise was repeated for datum temperature values of $0^{O}C$, $-5^{O}C$, and $-10^{O}C$.

This appendix presents the results in a tabulated format. The term referred to as the coefficient is the coefficient “A” in the above equation while the term “constant” refers to the regression constant “B” in the equation.

As noted earlier, the data for the samples cured at ambient conditions were very erratic and therefore not used in the analysis. However, the data is reported in the appendix.

Table D1. Compressive strength predictions using the Arrhenius Method for mixes 1 and 2 for a curing temperature of $10^{O}C$ using $23^{O}C$ as reference.

COMPRESSIVE STRENGTH FOR MIXES 1 AND 2 CURED AT 10C													
23 vs. 10C	**5000 J/mole Activation Energy**							**5000 J/mole Activation Energy**					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	707.76	391.36	3,395	2,928	16.0%		3 day	999.47	-1039.4	3,201	2,566	24.7%
	7 day	707.76	391.36	3,992	3,847	3.8%		7 day	999.47	-1039.4	4,176	4,154	0.5%
	14 day	707.76	391.36	4,483	-	-		14 day	999.47	-1039.4	4,738	4,706	0.7%
	28 day	707.76	391.36	4,995	-	-		28 day	999.47	-1039.4	5,428	5,511	-1.5%
	25000 J/mole Activation Energy							25000 J/mole Activation Energy					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	714.41	301.57	3,238	2,928	10.6%		3 day	1007.1	-1153.6	2,980	2,566	16.1%
	7 day	714.41	301.57	3,833	3,847	-0.4%		7 day	1007.1	-1153.6	3,944	4,154	-5.1%
	14 day	714.41	301.57	4,326	-	-		14 day	1007.1	-1153.6	4,520	4,706	-4.0%
	28 day	714.41	301.57	4,833	-	-		28 day	1007.1	-1153.6	5,204	5,511	-5.6%
	30000 J/mole Activation Energy							30000 J/mole Activation Energy					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	716.12	278.69	3,199	2,928	9.3%		3 day	1009.1	-1182.6	2,925	2,566	14.0%
	7 day	716.12	278.69	3,792	3,847	-1.4%		7 day	1009.1	-1182.6	3,886	4,154	-6.5%
	14 day	716.12	278.69	4,287	-	-		14 day	1009.1	-1182.6	4,465	4,706	-5.1%
	28 day	716.12	278.69	4,792	-	-		28 day	1009.1	-1182.6	5,148	5,511	-6.6%
	35000 J/mole Activation Energy							35000 J/mole Activation Energy					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	717.84	255.63	3,159	2,928	7.9%		3 day	1011	-1211.8	2,869	2,566	11.8%
	7 day	717.84	255.63	3,752	3,847	-2.5%		7 day	1011	-1211.8	3,826	4,154	-7.9%
	14 day	717.84	255.63	4,247	-	-		14 day	1011	-1211.8	4,410	4,706	-6.3%
	28 day	717.84	255.63	4,751	-	-		28 day	1011	-1211.8	5,090	5,511	-7.6%
	40000 J/mole Activation Energy							40000 J/mole Activation Energy					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		datum tem	coeff	constant	predicted	actual	error %
	3 day	719.58	232.39	3,119	2,928	6.5%		3 day	1013	-1241.3	2,813	2,566	9.6%
	7 day	719.58	232.39	3,711	3,847	-3.5%		7 day	1013	-1241.3	3,767	4,154	-9.3%
	14 day	719.58	232.39	4,207	-	-		14 day	1013	-1241.3	4,354	4,706	-7.5%
	28 day	719.58	232.39	4,710	-	-		28 day	1013	-1241.3	5,033	5,511	-8.7%
	45000 J/mole Activation Energy							45000 J/mole Activation Energy					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
	3 day	721.34	208.96	3,079	2,928	5.2%		3 day	1015	-1270.9	2,756	2,566	7.4%
	7 day	721.34	208.96	3,670	3,847	4.6%		7 day	1015	-1270.9	3,708	4,154	-10.7%
	14 day	721.34	208.96	4,167	-	-		14 day	1015	-1270.9	4,298	4,706	-8.7%
	28 day	721.34	208.96	4,668	-	-		28 day	1015	-1270.9	4,976	5,511	-9.7%

Table D2. Compressive strength predictions using the Arrhenius Method for mixes 1 and 2 for a curing temperature of 38^{O}C using 23^{O}C as reference.

COMPRESSIVE STRENGTH FOR MIXES 1 AND 2 CURED AT 38C

23 vs. 38C

5000 J/mole Activation Energy							**5000 J/mole Activation Energy**					
Mix 1 Compressive strength							Mix 2 Compressive strength					
age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
3 day	707.76	391.36	3,469	3,500	-0.9%		3 day	999.47	-1039.4	3,320	3,051	8.8%
7 day	707.76	391.36	4,078	4,209	-3.1%		7 day	999.47	-1039.4	4,283	3,693	16.0%
14 day	707.76	391.36	4,550	4,564	-0.3%		14 day	999.47	-1039.4	4,853	-	-
28 day	707.76	391.36	5,064	5,277	-4.0%		28 day	999.47	-1039.4	5,524	5,056	9.3%
25000 J/mole Activation Energy							25000 J/mole Activation Energy					
Mix 1 Compressive strength							Mix 2 Compressive strength					
age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
3 day	714.41	301.57	3,615	3,500	3.3%		3 day	1007.1	-1153.6	3,586	3,051	17.5%
7 day	714.41	301.57	4,269	4,209	1.4%		7 day	1007.1	-1153.6	4,484	3,693	21.4%
14 day	714.41	301.57	4,669	4,564	2.3%		14 day	1007.1	-1153.6	5,105	-	-
28 day	714.41	301.57	5,181	5,277	-1.8%		28 day	1007.1	-1153.6	5,691	5,056	12.6%
30000 J/mole Activation Energy							30000 J/mole Activation Energy					
Mix 1 Compressive strength							Mix 2 Compressive strength					
age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
3 day	716.12	278.69	3,652	3,500	4.3%		3 day	1009.1	-1182.6	3,654	3,051	19.8%
7 day	716.12	278.69	4,318	4,209	2.6%		7 day	1009.1	-1182.6	4,535	3,693	22.8%
14 day	716.12	278.69	4,699	4,564	3.0%		14 day	1009.1	-1182.6	5,169	-	-
28 day	716.12	278.69	5,210	5,277	-1.3%		28 day	1009.1	-1182.6	5,734	5,056	13.4%
35000 J/mole Activation Energy							35000 J/mole Activation Energy					
Mix 1 Compressive strength							Mix 2 Compressive strength					
age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
3 day	717.84	255.63	3,689	3,500	5.4%		3 day	1011	-1211.8	3,721	3,051	22.0%
7 day	717.84	255.63	4,366	4,209	3.7%		7 day	1011	-1211.8	4,585	3,693	24.2%
14 day	717.84	255.63	4,729	4,564	3.6%		14 day	1011	-1211.8	5,232	-	-
28 day	717.84	255.63	5,240	5,277	-0.7%		28 day	1011	-1211.8	5,776	5,056	14.2%
40000 J/mole Activation Energy							40000 J/mole Activation Energy					
Mix 1 Compressive strength							Mix 2 Compressive strength					
age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
3 day	719.58	232.39	3,726	3,500	6.5%		3 day	1013	-1241.3	3,790	3,051	24.2%
7 day	719.58	232.39	4,415	4,209	4.9%		7 day	1013	-1241.3	4,637	3,693	25.6%
14 day	719.58	232.39	4,759	4,564	4.3%		14 day	1013	-1241.3	5,297	-	-
28 day	719.58	232.39	5,270	5,277	-0.1%		28 day	1013	-1241.3	5,818	5,056	15.1%
45000 J/mole Activation Energy							45000 J/mole Activation Energy					
Mix 1 Compressive strength							Mix 2 Compressive strength					
age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
3 day	721.34	208.96	3,764	3,500	7.5%		3 day	1015	-1270.9	3,858	3,051	26.5%
7 day	721.34	208.96	4,465	4,209	6.1%		7 day	1015	-1270.9	4,688	3,693	27.0%
14 day	721.34	208.96	4,790	4,564	4.9%		14 day	1015	-1270.9	5,361	-	-
28 day	721.34	208.96	5,300	5,277	0.4%		28 day	1015	-1270.9	5,861	5,056	15.9%

Table D3. Flexural strength predictions using the Arrhenius Method for mixes 1 and 2 for a curing temperature of $10^{O}C$ using $23^{O}C$ as reference.

FLEXURAL STRENGTH FOR MIXES 1 AND 2 CURED AT 10C

23 vs. 10C

5000 J/mole Activation Energy							5000 J/mole Activation Energy					
Mix 1 Flexural strength							Mix 2 flexural strength					
age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
3 day	69.565	218.55	514	470	9.3%		3 day	96.747	64.491	475	397	19.7%
7 day	69.565	218.55	573	540	6.0%		7 day	96.747	64.491	569	520	9.5%
14 day	69.565	218.55	621	613	1.2%		14 day	96.747	64.491	624	580	7.5%
28 day	69.565	218.55	671	623	7.7%		28 day	96.747	64.491	690	657	5.1%
25000 J/mole Activation Energy							25000 J/mole Activation Energy					
Mix 1 Flexural strength							Mix 2 flexural strength					
age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
3 day	70.449	208.41	498	470	6.1%		3 day	97.772	51.72	453	397	14.3%
7 day	70.449	208.41	558	540	3.2%		7 day	97.772	51.72	547	520	5.2%
14 day	70.449	208.41	605	613	-1.4%		14 day	97.772	51.72	603	580	3.9%
28 day	70.449	208.41	655	623	5.1%		28 day	97.772	51.72	668	657	1.8%
30000 J/mole Activation Energy							30000 J/mole Activation Energy					
Mix 1 Flexural strength							Mix 2 flexural strength					
age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
3 day	70.681	205.78	495	470	5.2%		3 day	98.037	48.44	448	397	12.9%
7 day	70.681	205.78	554	540	2.5%		7 day	98.037	48.44	542	520	4.2%
14 day	70.681	205.78	600	613	-2.1%		14 day	98.037	48.44	597	580	3.0%
28 day	70.681	205.78	651	623	4.5%		28 day	98.037	48.44	663	657	0.9%
35000 J/mole Activation Energy							35000 J/mole Activation Energy					
Mix 1 Flexural strength							Mix 2 flexural strength					
age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
3 day	70.918	203.12	491	470	4.4%		3 day	98.307	45.123	442	397	11.5%
7 day	70.918	203.12	550	540	1.8%		7 day	98.307	45.123	536	520	3.1%
14 day	70.918	203.12	596	613	-2.8%		14 day	98.307	45.123	592	580	2.0%
28 day	70.918	203.12	647	623	3.9%		28 day	98.307	45.123	657	657	0.1%
40000 J/mole Activation Energy							40000 J/mole Activation Energy					
Mix 1 Flexural strength							Mix 2 flexural strength					
datum tem	coeff	constant	predicted	actual	error %		datum tem	coeff	constant	predicted	actual	error %
3 day	71.16	200.41	487	470	3.5%		3 day	98.58	41.77	437	397	10.1%
7 day	71.16	200.41	546	540	1.1%		7 day	98.58	41.77	530	520	2.0%
14 day	71.16	200.41	592	613	-3.4%		14 day	98.58	41.77	586	580	1.1%
28 day	71.16	200.41	643	623	3.2%		28 day	98.58	41.77	652	657	-0.8%
45000 J/mole Activation Energy							45000 J/mole Activation Energy					
Mix 1 Flexural strength							Mix 2 flexural strength					
age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %
3 day	71.407	197.66	483	470	2.7%		3 day	98.86	38.376	431	397	8.7%
7 day	71.407	197.66	542	540	0.3%		7 day	98.86	38.376	525	520	0.9%
14 day	71.407	197.66	588	613	-4.1%		14 day	98.86	38.376	581	580	0.2%
28 day	71.407	197.66	639	623	2.6%		28 day	98.86	38.376	646	657	-1.6%

Table D4. Flexural strength predictions using the Arrhenius Method for mixes 1 and 2 for a curing temperature of $38^{O}C$ using $23^{O}C$ as reference.

FLEXURAL STRENGTH FOR MIXES 1 AND 2 CURED AT 38C													
5000 J/mole Activation Energy							5000 J/mole Activation Energy						23 vs. 38C
Mix 1 Flexural strength							Mix 2 flexural strength						
age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %	
3 day	69.565	218.55	521	467	11.6%		3 day	96.747	64.491	486	403	20.6%	
7 day	69.565	218.55	581	577	0.7%		7 day	96.747	64.491	579	567	2.2%	
14 day	69.565	218.55	627	587	6.9%		14 day	96.747	64.491	635	733	-13.4%	
28 day	69.565	218.55	678	660	2.7%		28 day	96.747	64.491	700	760	-7.9%	
25000 J/mole Activation Energy							25000 J/mole Activation Energy						
Mix 1 Flexural strength							Mix 2 flexural strength						
age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %	
3 day	70.449	208.41	535	467	14.6%		3 day	97.772	51.72	511	403	26.7%	
7 day	70.449	208.41	599	577	3.9%		7 day	97.772	51.72	597	567	5.4%	
14 day	70.449	208.41	639	587	8.9%		14 day	97.772	51.72	659	733	-10.1%	
28 day	70.449	208.41	690	660	4.5%		28 day	97.772	51.72	716	760	-5.8%	
30000 J/mole Activation Energy							30000 J/mole Activation Energy						
Mix 1 Flexural strength							Mix 2 flexural strength						
age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %	
3 day	70.681	205.78	538	467	15.4%		3 day	98.037	48.44	517	403	28.2%	
7 day	70.681	205.78	604	577	4.7%		7 day	98.037	48.44	602	567	6.2%	
14 day	70.681	205.78	642	587	9.4%		14 day	98.037	48.44	665	733	-9.3%	
28 day	70.681	205.78	693	660	4.9%		28 day	98.037	48.44	720	760	-5.2%	
35000 J/mole Activation Energy							35000 J/mole Activation Energy						
Mix 1 Flexural strength							Mix 2 flexural strength						
age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %	
3 day	70.918	203.12	542	467	16.1%		3 day	98.307	45.123	524	403	29.8%	
7 day	70.918	203.12	609	577	5.6%		7 day	98.307	45.123	606	567	7.0%	
14 day	70.918	203.12	645	587	9.9%		14 day	98.307	45.123	671	733	-8.5%	
28 day	70.918	203.12	696	660	5.4%		28 day	98.307	45.123	724	760	-4.7%	
40000 J/mole Activation Energy							40000 J/mole Activation Energy						
Mix 1 Flexural strength							Mix 2 flexural strength						
age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %	
3 day	71.16	200.41	545	467	16.9%		3 day	98.58	41.77	530	403	31.4%	
7 day	71.16	200.41	614	577	6.4%		7 day	98.58	41.77	611	567	7.8%	
14 day	71.16	200.41	648	587	10.4%		14 day	98.58	41.77	677	733	-7.6%	
28 day	71.16	200.41	699	660	5.8%		28 day	98.58	41.77	728	760	-4.2%	
45000 J/mole Activation Energy							45000 J/mole Activation Energy						
Mix 1 Flexural strength							Mix 2 flexural strength						
age	coeff	constant	predicted	actual	error %		age	coeff	constant	predicted	actual	error %	
3 day	71.407	197.66	549	467	17.6%		3 day	98.86	38.376	536	403	33.0%	
7 day	71.407	197.66	618	577	7.2%		7 day	98.86	38.376	616	567	8.6%	
14 day	71.407	197.66	651	587	10.9%		14 day	98.86	38.376	684	733	-6.8%	
28 day	71.407	197.66	702	660	6.3%		28 day	98.86	38.376	733	760	-3.6%	

Table D5. Compressive strength predictions using the Arrhenius Method for mixes 1 and 2 cured in “ambient” conditions using $23^{O}C$ as reference.

COMPRESSIVE STRENGTH FOR MIXES 1 AND 2 CURED IN AMBIENT TEMPERATURE													
23 vs. Ambient	5000 J/mole Activation Energy							5000 J/mole Activation Energy					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		datum tem	coeff	constant	predicted	actual	error %
	3 day	707.76	391.36	3,418	3,234	5.7%		3 day	999.47	-1039.4	3,226	2,014	60.2%
	7 day	707.76	391.36	4,007	4,027	-0.5%		7 day	999.47	-1039.4	4,194	3,631	15.5%
	14 day	707.76	391.36	4,506	4,015	12.2%		14 day	999.47	-1039.4	4,768	3,758	26.9%
	28 day	707.76	391.36	5,020	4,892	2.6%		28 day	999.47	-1039.4	5,462	4,976	9.8%
	25000 J/mole Activation Energy							25000 J/mole Activation Energy					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		datum tem	coeff	constant	predicted	actual	error %
	3 day	714.41	301.57	3,356	3,234	3.8%		3 day	1007.1	-1153.6	3,117	2,014	54.8%
	7 day	714.41	301.57	3,909	4,027	-2.9%		7 day	1007.1	-1153.6	4,034	3,631	11.1%
	14 day	714.41	301.57	4,446	4,015	10.8%		14 day	1007.1	-1153.6	4,678	3,758	24.5%
	28 day	714.41	301.57	4,960	4,892	1.4%		28 day	1007.1	-1153.6	5,375	4,976	8.0%
	30000 J/mole Activation Energy							30000 J/mole Activation Energy					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		datum tem	coeff	constant	predicted	actual	error %
	3 day	716.12	278.69	3,341	3,234	3.3%		3 day	1009.1	-1182.6	3,093	2,014	53.6%
	7 day	716.12	278.69	3,885	4,027	-3.5%		7 day	1009.1	-1182.6	3,994	3,631	10.0%
	14 day	716.12	278.69	4,432	4,015	10.4%		14 day	1009.1	-1182.6	4,657	3,758	23.9%
	28 day	716.12	278.69	4,945	4,892	1.1%		28 day	1009.1	-1182.6	5,354	4,976	7.6%
	35000 J/mole Activation Energy							35000 J/mole Activation Energy					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		datum tem	coeff	constant	predicted	actual	error %
	3 day	717.84	255.63	3,326	3,234	2.9%		3 day	1011	-1211.8	3,068	2,014	52.3%
	7 day	717.84	255.63	3,861	4,027	-4.1%		7 day	1011	-1211.8	3,953	3,631	8.9%
	14 day	717.84	255.63	4,417	4,015	10.0%		14 day	1011	-1211.8	4,637	3,758	23.4%
	28 day	717.84	255.63	4,931	4,892	0.8%		28 day	1011	-1211.8	5,333	4,976	7.2%
	40000 J/mole Activation Energy							40000 J/mole Activation Energy					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		datum tem	coeff	constant	predicted	actual	error %
	3 day	719.58	232.39	3,312	3,234	2.4%		3 day	1013	-1241.3	3,045	2,014	51.2%
	7 day	719.58	232.39	3,837	4,027	-4.7%		7 day	1013	-1241.3	3,913	3,631	7.8%
	14 day	719.58	232.39	4,403	4,015	9.7%		14 day	1013	-1241.3	4,617	3,758	22.9%
	28 day	719.58	232.39	4,917	4,892	0.5%		28 day	1013	-1241.3	5,312	4,976	6.8%
	45000 J/mole Activation Energy							45000 J/mole Activation Energy					
	Mix 1 Compressive strength							Mix 2 Compressive strength					
	age	coeff	constant	predicted	actual	error %		datum tem	coeff	constant	predicted	actual	error %
	3 day	721.34	208.96	3,297	3,234	2.0%		3 day	1015	-1270.9	3,023	2,014	50.1%
	7 day	721.34	208.96	3,813	4,027	-5.3%		7 day	1015	-1270.9	3,873	3,631	6.7%
	14 day	721.34	208.96	4,390	4,015	9.3%		14 day	1015	-1270.9	4,598	3,758	22.4%
	28 day	721.34	208.96	4,903	4,892	0.2%		28 day	1015	-1270.9	5,291	4,976	6.3%

Table D6. Flexural strength predictions using the Arrhenius Method for mixes 1 and 2 cured in “ambient” conditions using 23^{O}C as reference.

FLEXURAL STRENGTH FOR MIXES 1 AND 2 CURED IN AMBIENT TEMPERATURE												
5000 J/mole Activation Energy							5000 J/mole Activation Energy					
Mix 1 Flexural strength							Mix 2 flexural strength					
datum tem	coeff	constant	predicted	actual	error %		datum tem	coeff	constant	predicted	actual	error %
3 day	69.565	218.55	516	295	74.9%		3 day	96.747	64.491	478	433	10.3%
7 day	69.565	218.55	574	450	27.6%		7 day	96.747	64.491	572	527	8.6%
14 day	69.565	218.55	623	500	24.6%		14 day	96.747	64.491	627	-	-
28 day	69.565	218.55	673	-	-		28 day	96.747	64.491	694	627	10.7%
25000 J/mole Activation Energy							25000 J/mole Activation Energy					
Mix 1 Flexural strength							Mix 2 flexural strength					
datum tem	coeff	constant	predicted	actual	error %		datum tem	coeff	constant	predicted	actual	error %
3 day	70.449	208.41	509	295	72.5%		3 day	97.772	51.72	469	433	8.2%
7 day	70.449	208.41	566	450	25.8%		7 day	97.772	51.72	561	527	6.5%
14 day	70.449	208.41	617	500	23.3%		14 day	97.772	51.72	618	-	-
28 day	70.449	208.41	667	-	-		28 day	97.772	51.72	685	627	9.2%
30000 J/mole Activation Energy							30000 J/mole Activation Energy					
Mix 1 Flexural strength							Mix 2 flexural strength					
datum tem	coeff	constant	predicted	actual	error %		datum tem	coeff	constant	predicted	actual	error %
3 day	70.681	205.78	507	295	71.9%		3 day	98.037	48.44	467	433	7.7%
7 day	70.681	205.78	564	450	25.4%		7 day	98.037	48.44	558	527	5.9%
14 day	70.681	205.78	615	500	23.0%		14 day	98.037	48.44	615	-	-
28 day	70.681	205.78	666	-	-		28 day	98.037	48.44	682	627	8.9%
35000 J/mole Activation Energy							35000 J/mole Activation Energy					
Mix 1 Flexural strength							Mix 2 flexural strength					
datum tem	coeff	constant	predicted	actual	error %		datum tem	coeff	constant	predicted	actual	error %
3 day	70.918	203.12	505	295	71.3%		3 day	98.307	45.123	465	433	7.2%
7 day	70.918	203.12	562	450	24.9%		7 day	98.307	45.123	555	527	5.4%
14 day	70.918	203.12	613	500	22.7%		14 day	98.307	45.123	613	-	-
28 day	70.918	203.12	664	-	-		28 day	98.307	45.123	680	627	8.5%
40000 J/mole Activation Energy							40000 J/mole Activation Energy					
Mix 1 Flexural strength							Mix 2 flexural strength					
datum tem	coeff	constant	predicted	actual	error %		datum tem	coeff	constant	predicted	actual	error %
3 day	71.16	200.41	504	295	70.7%		3 day	98.58	41.77	463	433	6.8%
7 day	71.16	200.41	560	450	24.5%		7 day	98.58	41.77	552	527	4.8%
14 day	71.16	200.41	612	500	22.4%		14 day	98.58	41.77	611	-	-
28 day	71.16	200.41	663	-	-		28 day	98.58	41.77	678	627	8.1%
45000 J/mole Activation Energy							45000 J/mole Activation Energy					
Mix 1 Flexural strength							Mix 2 flexural strength					
datum tem	coeff	constant	predicted	actual	error %		datum tem	coeff	constant	predicted	actual	error %
3 day	71.407	197.66	502	295	70.1%		3 day	98.86	38.376	461	433	6.3%
7 day	71.407	197.66	558	450	24.0%		7 day	98.86	38.376	549	527	4.3%
14 day	71.407	197.66	610	500	22.1%		14 day	98.86	38.376	609	-	-
28 day	71.407	197.66	661	-	-		28 day	98.86	38.376	675	627	7.8%

23 vs. Ambient

Appendix E – Comparison of Mix 2 Data with Data Collected in the University of California, Berkeley Study

The University of California, Berkeley (UCB) conducted a very comprehensive and detailed research project on concrete maturity involving both laboratory and field work (Mancio et al., 2004). The study used four different material sources, one of which was the source of mix used in the paving project near Victorville, CA. This mix design used by UCB from the Victorville, CA source is identical to mix 2 of this study. Tables E1 and E2 show a comparison of raw strength data obtained for the mix in the two concurrent projects.

Table E3 shows a summary of all the averages. Although not all measured strengths are directly comparable, excluding the extreme outliers that have been highlighted, the flexural strength values are reasonably close at the same age. The average ratio between closely comparable results, excluding the two UCB outliers, for flexural strength is 1.08 (Caltrans' results are higher by 8% on average). Likewise for compressive strength, although not all measured strengths are directly comparable, the relationship between compressive strengths is fair. The average ratio between closely comparable results for compressive strength is 1.21 (Caltrans results are higher by 21% on average).

The UCB study involved laboratory testing of concrete beam and concrete specimens (data for which have been presented in the tables referred to in the paragraphs above) to develop strength-maturity relationships for each mix and curing condition. Additionally, the study also involved recording maturity data in field pavement sections and testing of companion samples of field-cured cylinder and flexural beam specimens. Maturity measurements reported in the UCB report (Mancio et al., 2004) included maturity values calculated with the Nurse Saul function using the time-temperature history monitored in the field slabs using a datum temperature value of -10^{O}C.

Based on the strength-maturity relationships derived using lab data by the Caltrans team (relationships shown in Figure 17, Figure 18, Figure 19, and Figure 20), the Caltrans team used the maturity values collected from field data by UCB to predict the strength values of the field cured specimens. In principle, this is acceptable because the two mixes used by UCB and Caltrans were identical. Furthermore, this demonstrates how concrete maturity would be applied to predict in-situ strengths. This exercise provided an independent check to the calibration procedure and prediction process adopted by the Caltrans research team. Tables E4 and E5 show predicted flexural and compressive strengths, respectively, for different ages based on the UCB measured maturity measured in the field and the strength-maturity relationships derived by Caltrans for the same mix design. Adequate references are provided to the data obtained from the UCB report (Mancio et al., 2004).

The following issues are to be noted in reviewing the results presented in tables E4 and E5:

- The UCB derived Nurse-Saul equations were based on a regression analysis of curing results for all three temperature regimes in combination.
- The Caltrans derived Nurse-Saul equations were based on a regression analysis of standard 23^{O}C curing results only.
- The Caltrans derived Nurse-Saul equation tended to predict within 2-3 percent of actual field-measured compressive strengths.
- The UCB derived Nurse-Saul equation tended to predict too low by about 20% for actual field-measured compressive strengths.
- The Caltrans derived Nurse-Saul equation tended to predict about 10% percent too high compared to actual field-measured flexural strengths.
- The UCB derived Nurse-Saul equation tended to predict about 10% percent too high compared to actual field-measured flexural strengths.
- Standard curing strength test results, used alone to derive a Time-Temperature Factor (TTF, Nurse-Saul) in the laboratory, is adequate to predict high, low, and field-cured strengths.

Table E1. Flexural strength data of Victorville mix or Mix 2 determined from laboratory tests by UCB and Caltrans respectively.

FLEXURAL STRENGTH DATA, psi														
UCB RESULTS							**CALTRANS RESULTS**							
HOT CURING (40ºC for UCB, and 38ºC for Caltrans-ERES)														
Age (days)	**Trial A**	**Trial B**	**Average**	**Std. Dev.**	**COV**		**Age (days)**	**Trial A**	**Trial B**	**Trial C**	**Trial D***	**Average**	**Std. Dev.**	**COV**
3	425	462	**444**	26.09	5.9%		**3**	400	400	410	450	**415**	24	5.9%
7	527	543	**535**	11.65	2.2%									
							8	560	540	600	610	**578**	33	5.8%
14	612	569	**590**	30.22	5.1%		**14**	740	660	800	690	**723**	61	8.5%
							28	790	710	780	830	**778**	50	6.8%
31	1071	1182	**1126**	78.79	7.0%									
STANDARD CURING (23ºC)														
Age (days)	**Trial A**	**Trial B**	**Average**	**Std. Dev.**	**COV**		**Age (days)**	**Trial A**	**Trial B**	**Trial C**	**Trial D***	**Average**	**Std. Dev.**	**COV**
3	471	439	**455**	22.25	4.9%		**3**	500	470	490	460	**480**	18	3.8%
7	575	581	**578**	4.11	0.7%									
							8	540	580	580	560	**565**	19	3.1%
14	644	595	**619**	34.69	5.6%		**14**	610	630	630	600	**618**	15	1.5%
							28	700	700	710	610	**680**	47	6.7%
31	1217	1229	**1223**	9.00	0.7%									
COLD CURING (10ºC)														
Age (days)	**Trial A**	**Trial B**	**Average**	**Std. Dev.**	**COV**		**Age (days)**	**Trial A**	**Trial B**	**Trial C**	**Trial D***	**Average**	**Std. Dev.**	**COV**
							3	390	390	410	430	**405**	19	5.3%
4	361	338	**349**	16.74	5.5%									
8	403	481	**442**	54.82	12.4%		**8**	530	490	540	560	**530**	29	5.6%
							14	580	600	560	620	**590**	26	5.0%
18	501	549	**525**	34.11	3.6%									
							28	620	650	700	630	**650**	36	6.1%

* Specimen with maturity logger installed during casting.

Table E2. Compressive strength data of Victorville mix or Mix 2 determined from laboratory tests by UCB and Caltrans respectively.

COMPRESSIVE STRENGTH DATA, psi													
UCB RESULTS							**CALTRANS RESULTS**						
HOT CURING (40ºC for UCB, and 38ºC for Caltrans-ERES)													
Age (days)	**Trial A**	**Trial B**	**Average**	**Std. Dev.**	**COV**		**Age (days)**	**Trial A**	**Trial B**	**Trial C***	**Average**	**Std. Dev.**	**COV**
3	2578	2517	**2548**	43	1.7%		**3**	3035	3071	3311	**3139**	150	4.8%
7	3049	3598	**3324**	388	11.7%								
							8	3721	3664	3611	**3665**	55	1.5%
14	4388	4486	**4437**	69	1.6%		**14**	5231	5351	4562	**5048**	425	8.4%
							28	5125	4987	5337	**5150**	176	3.4%
31	5465	5484	**5475**	14	0.2%								

STANDARD CURING (23ºC)													
Age (days)	**Trial A**	**Trial B**	**Average**	**Std. Dev.**	**COV**		**Age (days)**	**Trial A**	**Trial B**	**Trial C***	**Average**	**Std. Dev.**	**COV**
3	2118	2404	**2261**	202	9.0%		**3**	3226	3290	2873	**3129**	224	7.2%
7	3106	2967	**3036**	98	3.2%								
							8	4205	4386	4053	**4215**	166	3.9%
14	3513	3961	**3737**	317	8.5%		**14**	4703	4637	4368	**4569**	177	3.9%
							28	5570	5510	5153	**5411**	226	4.2%
31	4000	4790	**4395**	559	12.7%								

COLD CURING (10ºC)													
Age (days)	**Trial A**	**Trial B**	**Average**	**Std. Dev.**	**COV**		**Age (days)**	**Trial A**	**Trial B**	**Trial C***	**Average**	**Std. Dev.**	**COV**
							3	2473	2659	2508	**2547**	99	3.9%
4	2010	2487	**2249**	337	15.0%								
8	3127	3303	**3215**	124	3.9%		**8**	4294	4014	4043	**4117**	154	3.7%
							14	4683	4729	4700	**4704**	23	0.5%
18	3903	3509	**3706**	279	7.5%								
							28	5539	5482	5316	**5445**	116	2.1%

* Specimen with maturity logger installed during casting

Table E3. Summary of strength comparisons

FLEXURAL STRENGTH DATA, psi					COMPRESSIVE STRENGTH DATA, psi				
UCB RESULTS		CALTRANS RESULTS		Strength Ratio CT/UCB	UCB RESULTS		CALTRANS RESULTS		Strength Ratio CT/UCB
HOT CURING (40ºC for UCB, and 38ºC for Caltrans-ERES)					HOT CURING (40ºC for UCB, and 38ºC for Caltrans-ERES)				
Age (days)	Avg Mr	Age (days)	Avg Mr		Age (days)	Avg f'c	Age (days)	Avg f'c	
3	444	3	415	0.93	3	2548	3	3139	1.23
7	535				7	3324			
		8	578	1.08			8	3665	1.10
14	590	14	723	1.22	14	4437	14	5048	1.14
		28	778				28	5150	
31	1126				31	5475			0.94
STANDARD CURING (23ºC)					STANDARD CURING (23ºC)				
Age (days)	Avg Mr	Age (days)	Avg Mr		Age (days)	Avg f'c	Age (days)	Avg f'c	
3	455	3	480	1.06	3	2261	3	3129	1.38
7	578				7	3036			
		8	565	0.98			8	4215	1.39
14	619	14	618	1.00	14	3737	14	4569	1.22
		28	680				28	5411	
31	1223				31	4395			1.23
COLD CURING (10ºC)					COLD CURING (10ºC)				
Age (days)	Avg Mr	Age (days)	Avg Mr		Age (days)	Avg f'c	Age (days)	Avg f'c	
		3	405	1.16			3	2547	1.13
4	349				4	2249			
8	442	8	530	1.20	8	3215	8	4117	1.28
		14	590				14	4704	
18	525				18	3706			
		28	650				28	5445	

Table E4. Summary of flexural strength predictions

	Flexural Strength Predictions							Ratio to actual strength	
	UCB measured TTF	UCB Prediction in MPa	UCB Prediction in psi	ERES prediction in MPa	ERES prediction in psi	Actual Strength in MPa	Actual Strength in psi	UCB	ERES
Table 11 in UCB report (Mancio et al., 2004)	2713	2.42	351	3.35	486	2.7	392	0.90	1.24
	6689	4.09	593	3.96	575	3.7	537	1.11	1.07
	9732	4.79	695	4.22	612	4.1	595	1.17	1.03
	27516	6.71	973	4.92	714	4.4	638	1.53	1.12
Table 13 in UCB report (Mancio et al., 2004)	2564	2.91	422	3.31	480	2.7	392	1.08	1.23
	6689	3.62	525	3.96	575	3.7	537	0.98	1.07
	9732	3.92	568	4.22	612	4.1	595	0.96	1.03
	27516	4.74	687	4.92	714	4.4	638	1.08	1.12

Table E5. Summary of compressive strength predictions

	Compressive Strength Predictions							Ratio to actual strength	
	UCB measured TTF	UCB Prediction in MPa	UCB Prediction in psi	ERES prediction in MPa	ERES prediction in psi	Actual Strength in MPa	Actual Strength in psi	UCB	ERES
Table 11 in UCB report (Mancio et al., 2004)	2713	NA	NA	22.91	3322	23.5	3408	NA	0.97
	6689			29.21	4235	31.7	4597		0.92
	9732			31.83	4615	33.6	4872		0.95
	27516			39.08	5666	37.2	5394		1.05
Table 13 in UCB report (Mancio et al., 2004)	2564	16.96	2459	22.52	3265	23.5	3408	0.72	0.96
	6689	23.51	3409	29.21	4235	31.7	4597	0.74	0.92
	9732	26.25	3806	31.83	4615	33.6	4872	0.78	0.95
	27516	33.83	4905	39.08	5666	37.2	5394	0.91	1.05

Appendix F – Procedure to Predict Strength Using Concrete Maturity

This appendix gives a brief description of the step-by-step procedure to be followed in developing a strength-maturity relationship, and subsequently to predict in-situ concrete strength based on field-recorded maturity readings. An example data set from the current study is utilized for this purpose. California Test Method (CTM) 524, presently being drafted, will be the standard test procedure followed to perform these tests.

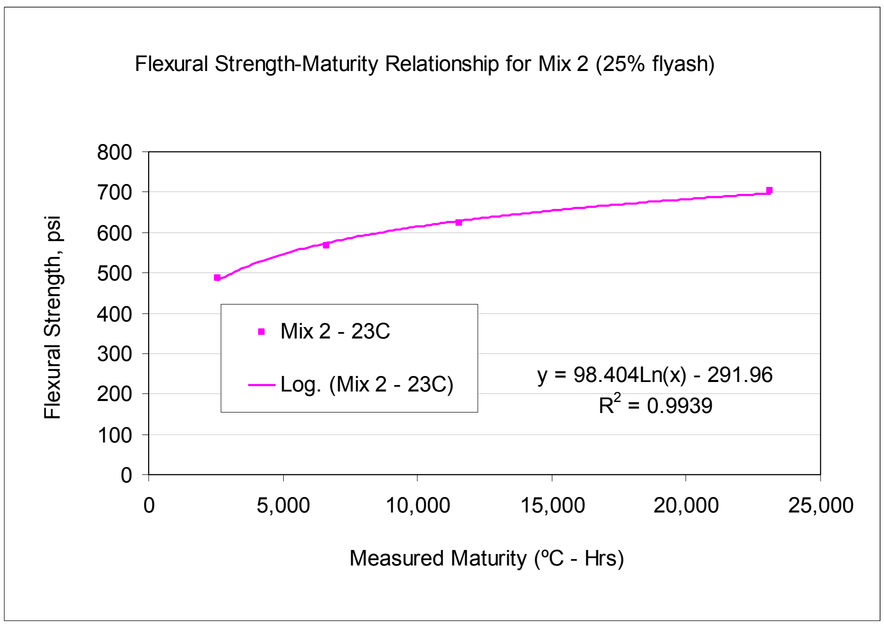
The strength prediction process will include both laboratory- and field-testing procedures. The laboratory test procedure will involve recording temperature (or maturity) data and performing strength tests on standard specimens at different ages. When this procedure is used to determine flexural strength, standard flexural beam specimens will be prepared, stored, and tested. When used to determine compressive strength, standard cylinder specimens will be prepared, stored, and tested. The field procedure will involve recording maturity readings in in-situ concrete from the time of concrete placing.

The following steps describe the laboratory test procedure. Mix 2 flexural strength data is used as an example to demonstrate the process.

1. Using the mix design proposed for a project, cast standard flexural beam specimens in the laboratory. The number of specimens cast will depend on the number of test ages selected for developing the strength-maturity relationship, and the number of test repetitions. For example, to test at 4 different test ages, cast a total of 18 beams – 16 for flexural strength testing and two for embedding maturity loggers. The 16 beams without maturity loggers will be tested, 4 each at 4 different ages.
2. Install maturity loggers in the specimens cast for this purpose in accordance with CTM 524. Record temperature readings from the time of casting until the time of last strength test. Store all specimens in a standard temperature- and humidity-controlled chamber, i.e. at 23^{O}C (73^{O}F) and 100 percent relative humidity. Note that if there is inadequate moisture for curing, the maturity results will not be valid.
3. If only temperature measurements are recorded, calculate the cumulative maturity at each time interval using the selected maturity function, using either the Nurse-Saul or Arrhenius function.
4. Perform strength tests at the selected test ages (minimum 4 test ages).
5. Develop the strength-maturity relationship using a logarithmic model. For example, with mix 2's flexural strength the following maturity and strength values were obtained for the specimens stored in the standard fog room:

Test age (days)	Maturity – TTF (degC-hour)	Flexural strength (psi)
3	2,579	487
8	6,614	567
14	11,551	623
28	23,097	703

Plotting maturity values on the abscissa and flexural strength values on the ordinate, add a trend line using the MS Excel built-in function. Select a logarithmic model and opt to view the equation and the R-squared for the model developed as shown below:



The logarithmic model, *y = 98.404*log(x) - 291.96*, is the strength-maturity relationship, where:

y = Flexural strength, psi
x = Maturity expressed as Temperature-Time Factor in deg C- hour

The field procedure involves the following steps:

1. For a concrete structure built with the same mix design, place maturity loggers in the field at the time of concrete placement.
2. Record maturity over time as the concrete cures and hardens.
3. To estimate the strength attained by the concrete mix at any time, use the maturity value recorded at the given time and substitute in the logarithmic model developed for the mix. For example, the same mix cured at a lower

temperature could result in a maturity value of 3,953 degC-hour at 7 days. The estimated strength in this case would be:

*Mr at 7 days = 98.404*log (3953) - 291.96 = 542 psi*